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UNITED STATES ARMY COMBAT DEVELOPMENTS COMMAND

VERTICAL FLIGHT PERFORMANCE CRITERIA

PREPARED BY

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UNITED STATES ARMY COMBAT DEVELOPMENTS COMMAND

AVIATION AGENCY

APPROVED FINAL REPORT

JUNE 1968

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ACKNOWLEDGEMENT

The conclusions and recommendations of this study have been approved by the Commanding General, United States Army Combat Developments Command. This approved study report supersedes all previous editions. This study is based on information gathered and analysis performed primarily by the author, Mr. Richard S. Maccabe, United States Army Combat Developments Command Aviation Agency.

The many contributions received from the aircraft industries, other government activities, and officers assigned to the Aviation Agency are gratefully acknowledged.

VERTICAL FLIGHT PERFORMANCE CRITERIA

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ABSTRACT

Various problems confronting the military operators of VTOL aircraft in tactical environments which tend to impede the ability to hover and perform related vertical flight maneuvers are examined. Several modes of flight employed under certain tactical situations were examined to establish appropriate power and lift requirements in excess of those required to hover. The influences of adverse ambient temperature, high elevation, wind, aircraft and engine deterioration, periodic aircraft weight increases, and operator skill levels are evaluated. These factors are appropriately interrelated and allowances are suggested to provide continued satisfactory vertical flight performance in service. Recommended vertical performance criteria for application in concept formulation studies, materiel requirements, and specifications for future Army tactical VTOL aircraft are provided.

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VERTICAL FLIGHT PERFORMANCE CRITERIA STUDY

SUMMARY

1. PROBLEM

To establish criteria which define the mission essential vertical flight performance requirements for Army tactical helicopters and V/STOL aircraft.

2. BACKGROUND

A study conducted in 1965 by the Combat Operations Research Group (CORG) challenged the validity of the traditional Army hot day criteria for rotary wing aircraft, and resulted in the reduction of the hover criteria in several recent requirements for new aircraft. The CORG Study defined hover performance solely on the basis of ambient temperature and elevation effects. Since there are other factors which influence vertical flight performance, any aircraft designed to the CORG criteria would be unable to operate as intended in the specified environment. The need to recognize and accommodate these other factors prompted the conduct of the subject study as an in-house effort.

3. PURPOSE AND OBJECTIVE

The vertical flight performance criteria will be sufficient to accommodate the various adversities presented by environment, mission requirements, growth potential, and service operator skill levels, yet avoid inefficiency resulting from overdesign. The selected criteria will be identified for use in concept formulation studies, qualitative materiel requirements (QMR) for future aircraft, and aircraft model specifications as an item of guaranteed performance.

4. SCOPE AND METHOD

The operating environment for this study was defined using existing studies which established occurrences of extreme temperatures and elevations in areas of the world most likely to require U. S. military support. Downdrafts encountered in natural gusts and in the wakes of preceding aircraft were defined in a similar manner. Experienced military aviators were interviewed to determine the type and nature of typical maneuvers performed under tactical mission conditions. Aircraft and engine deterioration and growth trends were established based on experience with current inventory aircraft. Aircraft accidents and their causes were examined to demonstrate the need for adequate vertical flight

performance capabilities. Criteria were ultimately developed which could accommodate these influences and requirements.

5. DISCUSSION

Several factors which influence the vertical performance capabilities of Army tactical helicopters were discussed. The magnitude of each influence was evaluated wherever possible to provide a basis of establishing suitable performance criteria. These influences are--

a. Ambient Conditions. The ambient surveys examined support an environment of not less than 4,000 feet/95° F. as the ambient baseline upon which the vertical performance criterion may be developed.

b. Vertical Climb Performance. A requirement for a vertical climb capability of not less than 500 fpm OGE at zero airspeed was developed to permit operation into and out of congested landing zones. This capability will minimize exposure time to enemy action, accommodate wind gusts encountered in moderate turbulence and downdrafts in the wakes of preceding helicopters, provide a capability to abort the landing from a steep final approach, and provide adequate control power for maneuvering or stabilizing the aircraft.

c. Performance Deterioration in Service. The performance capabilities of any helicopter are degraded by erosion of the airframe and engine(s) accumulated during a period of service. The rate of this deterioration depends primarily upon the presense of sand and dust in operating areas, and upon protective devices incorporated on the aircraft. Maintenance practices in the more remote areas in which Army tactical helicopters are operated may also contribute to reduced performance. Rotor blade erosion has been found to increase the power required to hover; however, this increase probably does not exceed approximately 1 percent before blades are replaced. Engine power available may be decreased from 4 to 9 percent by erosion before the engine is removed and replaced. The imposition of a 5 percent power allowance to accommodate engine erosion, airframe/rotor blade erosion, and losses attributed to maintenance problems is conservative, but should be sufficient for aircraft of the future.

d. Aircraft Weight Growth. Aircraft weight growth results from service (repairs), mission changes (expansion), and design improvements (changes incorporated during production and in service). Weight increases at a rate of from 1 to 2 percent per year, depending on the initial size of the aircraft and its versatility or adaptability to perform other missions. Since the Army utilizes a given aircraft model at least 10 years, weight increments of from 10 to 20 percent above initial design empty weight should be anticipated by the user and the

developer. This factor may be overcome by insuring that the design has adequate growth potential in engines, transmissions, components, and airframe structure.

6. COORDINATION

A preliminary study report was prepared in September 1967, and provided to the major helicopter manufacturers and appropriate military activities for review. Comments received were used to revise this study. The findings and recommendations of the coordinated study were presented to the Commanding General, U.S. Army Combat Developments Command; Deputy Commanding General, U.S. Army Materiel Command; Office of the Assistant Chief of Staff for Force Development; and Offices of the Secretary of Defense and Secretary of the Army on 8 December 1967. It was agreed that aircraft growth potential should be recognized philosophically as a matter to be controlled by the developing activity. Thus, no magnitude would be specified in the criteria. It was also suggested that the criteria be based upon the use of Normal Rated Power to promote engine longevity. These changes were incorporated into a final draft study report published in January 1968. Technical analyses were conducted by the Aviation Agency using helicopter designs provided by the U.S. Army Aviation Materiel Laboratories to assess the impact of normal rated power rather than military rated power as the design requirement. These analyses indicated that the aircraft size, gross weight, and cost would be substantially increased to accommodate the larger, more powerful engine(s) installed to meet this requirement. Based on these analyses, the Aviation Agency resubmitted the study in February 1968, and requested that the power requirement reflect the use of military rated power in the interests of efficiency and economy. This revised vertical flight performance criteria study report was approved by Headquarters, U.S. Army Combat Developments Command in June 1968.

7. CONCLUSIONS AND FINDINGS

a. The establishment of Army "hot day" performance requirements in terms of pressure altitude and ambient temperature conditions is not sufficient in itself to define performance requirements for Army tactical VTOL aircraft. Vertical flight performance requirements must be designed to permit accomplishment of the various essential vertical flight maneuvers under adverse ambient and environmental conditions and must provide for the continuation of these capabilities throughout the aircraft's service life.

b. Criteria based on the ability to hover and climb vertically OGE under adverse ambient conditions, with power reserves for engine and airframe

deterioriation, and growth potential for future needs are required for defining the suitable vertical flight performance requirements of Army tactical VTOL aircraft.

8. RECOMMENDATIONS

a. The following criteria be adopted as the USACDC standard for vertical flight performance to be applied to concept formulation studies, QMR, and model specifications for all subsequent Army tactical rotary wing and other V/STOL aircraft:

> "The aircraft shall be capable of hovering out of ground effect (OGE) under zero wind, 4,000 feet pressure altitude, 95° F. temperature conditions at the basic mission gross weight, and achieve a 500 feet per minute vertical climb at zero airspeed under these conditions, using not more than 95 percent of engine military rated power."

> "The aircraft shall be designed with adequate structure and growth potential in engine(s) and transmission(s) to accommodate future increased gross weight."

b. It is further recommended that consideration be given to the use of 4,000 feet pressure altitude at 95° F. ambient temperature conditions in lieu of standard sea level conditions to define those performance requirements for Army tactical VTOL aircraft which are not covered by the vertical flight performance criteria. This will provide consistency between the different performance parameters and will serve to relate aircraft specified performance to the intended mission and environmental situations.

VERTICAL FLIGHT PERFORMANCE CRITERIA STUDY

1. PROBLEM

To establish criteria which define the mission essential vertical flight performance requirements for Army tactical helicopters and appropriate V/STOL aircraft.

2. SCOPE AND OBJECTIVE

The criteria must be sufficient to accommodate the various adversities presented by environment, mission requirements, growth potential, and service operator skill levels, yet avoid inefficiency resulting from overdesign. The selected criteria will be identified for use in concept formulation studies, qualitative materiel requirements (QMR) for future aircraft, and in aircraft model specifications as an item of guaranteed performance.

3. ASSUMPTIONS

a. The requirement for vertical performance capabilities is valid; thus, the penalties inherent in VTOL designs are justified.

b. The Army must be capable of operating anywhere in the world--day and night--and under most unfavorable weather situations.

c. The traditional hover criterion, expressed in terms of ambient variations, appears to be often misunderstood. This is evidenced by the fact that most studies concerned with helicopter hover requirements have dwelled solely on the probable occurrence of limiting ambient conditions and relating these phenomena to the pure hovering mode of operation without regard to other vertical flight modes such as ascent, descent, or gust response.

d. Army tactical aircraft will be powered by turbine engines throughout the foreseeable future.

4. DISCUSSION

a. Introduction.

(1) Since the helicopter was first employed in a military role, it has been used to gain access to sites inaccessible to other transportation means. With the adoption of the airmobility concept by the Army in 1962, the helicopter has provided a quick-reaction capability for the rapid displacement of ground combat units unencumbered by most natural barriers.

(2) The missions conducted by airmobile units often entail operating into and out of closely confined areas which necessitate steep approaches and near vertical landings and takeoffs. At times, terrain slope, pinnacles, inundation, or foliage may even preclude landings, and loading and off-loading operations must be accomplished from a hover. This ability to hover is the most evident characteristic identified with the helicopter. Thus, helicopter vertical performance requirements have generally been considered in terms of this capability.

(3) There are several distinct factors which affect the ability of an aircraft to hover. These factors include ambient temperature, pressure, density, turbulence, and wind; engine and airframe condition; proximity to the ground; pilot skill; and aircraft loading. The user has some measure of control over all but the ambient conditions; thus, criteria for hovering are generally specified in terms of the ambient conditions. Since hovering may be required at various heights above the ground, and operation in close proximity to the ground (i.e., within a height of up to approximately one rotor diameter's measure) has been found to enhance hover performance, the additional constraints of in ground effect (IGE) or out of ground effect have been applied to better define the hover criteria.

(4) The Army has employed a hot-day criterion which requires the ability to hover OGE with no wind under ambient pressure altitude and temperature conditions of 6,000 feet/95° F. This criterion was established by military users based upon their operational experience and judgment. When subjected to the close scrutinization of Military and Department of Defense evaluators using cost effectiveness analysis techniques, certain excesses have been indicated, and the validity of this requirement has been challenged. A study conducted by the Combat Operations Research Group (CORG) concluded that a 4,000 feet/95° F. hover OGE criterion is sufficient when based solely on the probabilities of encountering various limiting ambient conditions not more than 5 percent of the time of the year in those countries which are contiguous to the Sino-Soviet Bloc countries. 1/ Although it was never approved by the Department of the Army,

this study was instrumental in the downgrading of hover requirements expressed in several recent QMR for Army aircraft systems; and hover OGE requirements for 4,000 feet/95° F., and 5,000 feet/90° F. have been substituted for the original requirement of 6,000 feet/95° F. This apparent lack of consistency was criticized by the Office of the Chief of Research and Development, Department of the Army. 2/

b. Summary of Applicable Studies Conducted to Date. The following three studies are considered in the preparation of this study of vertical performance requirements:

(1) Research Study Report RER-32, HQ, U.S. Army Quartermaster Research and Engineering Command, U.S. Army Quartermaster Research and Engineering Center, March 1963, subject: Temperature and Density Altitude Considerations for Design of Army Helicopters. The study conducted by the Quartermaster Research and Engineering Center presents data on the percentage of time during the warmest month that temperatures of 80°, 85°, 90°, 95°, 100°, and 105° F. are exceeded in selected stations located in moderately high elevation areas throughout the world between latitudes 45° N and 45° S. The warmest month's mean daily maximum temperature, absolute maximum daily temperature, and elevation (pressure altitude) are also presented. High temperatures at moderate elevations were found to occur most frequently in the southern portions of Asia and North America. Kerman, Iran, reported an elevation of 6,100 feet and temperatures above 95° F. occurred 18 percent of the time in July. Its average daily maximum temperature during that month was 101° F. Kabul, Afghanistan, at 5,895 feet elevation, reported a mean daily maximum temperature in July of 92° F., and temperatures in excess of 95° F. 6 percent of the time. These two stations were considered indicative of those locales. In central Mexico, two stations reported extremely high temperatures. Camargo, at 5,423 feet, experienced a mean daily maximum temperature of 108° F. during June, and exceeded 95° F. nearly one-quarter of that month. Lagos, at 6,138 feet, exceeded 95° F. 11 percent of the time during June.

(2) Combat Operations Research Group Memorandum CORG-M-214, 15 July 1965, subject: Utility/Tactical Transport Requirements Study.

(a) The CORG study attempted to establish hovering design criteria on the basis of providing a 95 percent probability of hovering OGE in those nations contiguous to the Sino-Soviet border. Three hover design points were considered: 6,000 feet/95° F., 4,000 feet/95° F., and 2,700 feet/95° F. The study predicted the probabilities of encountering suitable ambient conditions for hovering (i.e., probability of not exceeding each of the three design points) throughout the year, using random daytime temperature/elevation samples obtained in selected areas

of each nation. The data were weighted on the basis of the sampled land area relative to the total land area of the country, and a representative temperature/altitude probability was established. Data generated in this manner are considered to be conservative for two reasons. First, the aircraft may be incapable of accomplishing assigned missions for weeks at a time if the occurrence of higher than design temperature/altitude conditions (5 percent of the year) is consecutive. Second, the significance of those small areas within a country that encounter extremes in temperature and altitude is lost when the weighted average is applied. Such conditions are found in the mountainous areas that separate much of the Communist and non-Communist nations in Southeast Asia and it is reasonable to anticipate requirements for U.S. Army support in these areas. The majority of nations considered, however, also include large areas that are far more favorable to helicopter operations, but which are much less likely to require the airmobility advantages provided by Army helicopters.

(b) The conclusions of the CORG Study are that--

1. The overall daytime probabilities of hovering OGE in areas adjacent to the Sino-Soviet Bloc for 6,000 feet/95° F., 4,000 feet/95° F., and 2,700 feet/95° F. design points are .99, .95, and .90, respectively. On a 24-hour day, full year basis (assuming 100 percent probability at night), hover probabilities are .995, .975, and .950, respectively.

2. The hover probabilities of 100 percent occur in 12 nations at 6,000 feet/95° F., 7 nations at 4,000 feet/95° F., and 4 nations at 2,700 feet/95° F. in the 16 nations/areas considered.

3. A hover probability of .95 is suitable for Army helicopter design. This suggested adoption of the 4,000 feet/95° F. design criteria.

(3) Boeing-Vertol Report SM-663, 10 January 1964, subject: Investigation of the Hovering Environment for Military VTOL Aircraft in World Wide Operations.

(a) The approach taken by Boeing-Vertol was to first determine the potential areas of conflict throughout the world which would necessitate use of the helicopter rather than fixed wing aircraft for containment. These countries are located within a band of 1,500 nautical miles either side of the equator. Since use of helicopters is most appropriate primarily in areas in which the terrain precludes use of fixed wing aircraft and surface vehicles, the mean daily maximum temperature data for the hottest month in those specific areas was adopted rather than the land area weighting technique employed by CORG. The

methodology employed by Boeing-Vertol resulted in somewhat more frequent occurrences of unfavorable ambient conditions than did the CORG Study.

(b) Table I and figures 1 through 5 illustrate the probable occurrences of surface temperatures during the hottest month of the year in the eastern Mediterranean, Southwest Asia, Southeast Asia, Iran Saudi Arabia, and Pakiston-Afghanistan areas, respectively.

(c) This study concluded that a helicopter designed to the Army's 6,000 feet/95° F. hover criteria could successfully carry its design payload in 87 percent of the reporting areas. (See table II and figure 6.)

It must be emphasized that these three studies make no allowance for operational problems or flight modes other than the static conditions of hovering OGE based solely on the influence of ambient conditions.

c. Hover Performance.

(1) The basic advantage of the helicopter over other aircraft types is its ability to hover. The helicopter achieves its hover capability at the lowest cost in terms of installed shaft horsepower (shp) of any known VTOL aircraft design. This is because the power required to hover at a given gross weight depends upon rotor hovering efficiency (referred to as rotor figure of merit), rotor disc loading (aircraft gross weight divided by the swept area of the rotor blades), and ambient air density. The equations for power loading expressed as pounds of aircraft gross weight per rotor shaft horsepower (lb/shp) at hover was derived as shown in annex A as:

$$P.L. = 37.7M \frac{\sqrt{\sigma}}{\sqrt{w}} (1-\eta)$$

Where P. L. = rotor power loading, lb/shp.

M = rotor figure of merit.

w = rotor disc loading, lb/ft^2.

σ = ambient density ratio at actual density altitude (ρ/ρ_{ssl}): the ratio of airmass density at altitude (ρ) to airmass density at standard sea level conditions (ρ_{ssl} = 0.002378 slugs/ft^3).

η = power losses from transmission, tail rotor, and accessories.

TABLE I

SURFACE TEMPERATURE/ELEVATION DATA FOR THE EASTERN MEDITERRANEAN

City	Country	Elevation Ft.	Hottest Month	Max. °F	Mean °F	Min °F	MDM °F	MDM Over Hottest Season 2 Mo °F	MDM Over Hottest Season 3 Mo °F
Erzurum	Turkey	6,402	Aug	93	65.5	37	78	2	8
Kars	Turkey	5,741	Aug	94	63	33	77	2	8
Van	Turkey	5,682	Aug	93	70	45	83	0	7
Sivas	Turkey	3,888	Aug	98	65.5	37	81	1	7
Konya	Turkey	3,363	Jul	100	72.5	44	86	1	6
Usak	Turkey	3,022	Aug	99	72	44	86	1	7
Ankara	Turkey	2,825	Aug	100	72.5	44	86	1	9
Kastamonu	Turkey	2,592	Aug	100	67	41	81	1	6
Damascus	Syria	2,362	Aug	102	76	48	91	3	8
Deirezzor	Syria	699	Jul	111	84.5	45	99	1	6
Bursa	Turkey	528	Aug	106	75	47	87	0	5
Trabzon	Turkey	354	Aug	101	73.5	56	79	1	5
Zonguldak	Turkey	138	Jul	104	69	50	76	1	5
Antalya	Turkey	131	Jul	110	83	59	93	1	7
Beirut	Lebanon	111	Aug	98	80	64	87	2	3
Izmir	Turkey	92	Aug	108	80.5	57	92	0	5
Adana	Turkey	82	Aug	106	82	57	93	1	3
							AVERAGE	1.1	6.2

TABLE I (CONT)

SURFACE TEMPERATURE/ELEVATION DATA FOR SOUTHWEST ASIA

City	Country	Elevation Ft.	Hottest Month	Max. °F	Mean °F	Min °F	MDM °F	MDM Over Hottest Season 2 Mo. °F	MDM Over Hottest Season 3 Mo. °F
Lhasa	Tibet	12,090	Jun	89	68	36	75	1	3
Leh	Kashmir	11,503	Jul	88	63.5	33	77	2	7
Kerman	Iran	6,100	Jul	109	83	49	101	0	3
Kabul	Afghanistan	5,955	Jul	101	76.5	51	92	1	5
Isfahan	Iran	5,817	Jul	110	77	48	92	2	6
Quetta	Pakistan	5,490	Jul	104	80	47	95	2	2
Srinagar	Kashmir	5,205	Jul	99	76.5	52	88	1	3
Kermanshah	Iran	4,285	Jul	103	68.5	31	90	2	9
Tehran	Iran	4,002	Jul	107	79.5	51	93	2	6
Kandahar	Afghanistan	3,462	Jul	108	84	53	102	3	3
Hail	Saudia Arabia	3,185	Aug	109	85.5	53	101	1	1
Meshed	Iran	3,104	Jul	104	74.5	42	89	2	3
Ksara	Lebanon	3,018	Aug	104	75.5	50	90	3	4
Amman	Jordan	2,548	Aug	109	74	46	87	1	2
Rutba	Iraq	2,019	Aug	112	81	54	97	1	5
Seistan	Iran	2,000	Jul	118	91.5	63	87.5	3	3
Riyadh	Saudia Arabia	1,938	Jul	113	92	67	107	0	0
Indore	India	1,823	May	114	89.5	64	103	4	7
Hyderabad	Pakistan	1,778	May	112	92	67	104	3	7
Urfa	Turkey	1,772	Jul	115	88	48	102	1	7
Jaipur	India	1,431	May	118	91.5	60	105	2	6
Jubbulpore	India	1,327	May	114	91.5	66	106	5	8
Haleb	Syria	1,280	Aug	117	78.5	48	94	0	3
Peshawar	Pakistan	1,161	Jun	120	91.5	65	106	3	7
Nagpur	India	1,025	May	118	95.5	67	109	4	9
Raipur	India	970	May	117	94.5	67	107	4	9
Jodhpur	India	780	May	120	92	66	105	1	6
Bikaner	India	734	Jun	121	94	62	107	0	5
Mosul	Iraq	730	Aug	115	84	50	103	1	7
New Delhi	India	714	May	115	92	65	105	3	8
As Sulman	Iraq	662	Aug	115	87.5	62	105	1	6
Agra	India	554	May	117	92	66	107	2	6
Cawnpore	India	416	May	116	92.5	65	106	4	5
Multan	Pakistan	413	Jun	121	96	59	108	1	4
Gaya	India	365	May	116	94.5	67	106	4	5
Allahbad	India	322	May	116	94.5	67	107	4	4
Jacobabad	Pakistan	186	Jun	127	99.5	72	114	3	5
Patna	India	173	May	114	90	63	101	2	4
Ahmadabad	India	163	May	114	93	70	107	3	6
Habbaniya	Iraq	146	Jul	120	89.5	60	106	0	5
Baghdad	Iraq	111	Aug	119	89	58	105	0	5
Hyderabad	Pakistan	96	May	122	93.5	73	105	2	5
Shaibah	Iraq	60	Aug	121	92	64	107	1	5
Bandar	Iran	29	Jun	119	91	74	101	1	1
Kuwait	Arabia	16	Aug	119	90	72	98	1	3
Abadan	Iran	7	Aug	118	93	67	108	1	5
							AVERAGE	1.9	5.1

TABLE I (CONT)

SURFACE TEMPERATURE - ELEVATION DATA FOR SOUTHEAST ASIA

City	Country	Elevation Ft	Hottest Month	Max °F	Mean °F	Min °F	MDM °F	MDM Over Hottest Season 2 Mo °F	MDM Over Hottest Season 3 Mo °F
Kunming	China	6,211	Aug	91	69.5	48	77	0	0
Tengchung	China	5,360	Aug	87	68	51	74	1	1
Mengtzu	China	4,100	Aug	98	74.5	51	84	1	1
Lashio	Burma	2,802	Apr	99	75.5	54	89	2	3
Luang Prabang	Laos	942	Apr	113	82.5	57	96	1	3
Lungchow	China	873	Aug	103	81.5	63	89	1	1
Nakorn Rajasima	Thailand	554	Apr	108	86	60	98	0	3
Vientiane	Laos	531	Apr	104	79	54	91	2	3
Bhamo	Burma	386	May	106	83	62	93	0	4
Mandalay	Burma	252	Apr	111	88.5	69	96	3	4
Amherst	Burma	71	Apr	96	84.5	72	91	2	3
Cap-Saint-Jacques	Viet Nam	60	Apr	100	83	69	89	0	2
Hanoi	Viet Nam	53	Jun	104	85	69	92	1	2
Diamond Is	Burma	41	Apr	98	83.5	69	88	0	3
Saigon	Viet Nam	30	Apr	104	85.5	68	95	2	3
Qui Nhon	Viet Nam	20	Aug	106	87	69	95	2	2
Rangoon	Burma	18	Apr	106	86.5	68	97	1	5
Bangkok	Thailand	7	Apr	106	85	71	93	2	2
							AVERAGE	1.2	2.5

FIGURE 1

SURFACE TEMPERATURES FOR GIVEN PROBABILITIES OF NOT BEING EXCEEDED IN THE EASTERN MEDITERRANEAN AREA DURING THE HOTTEST MONTH

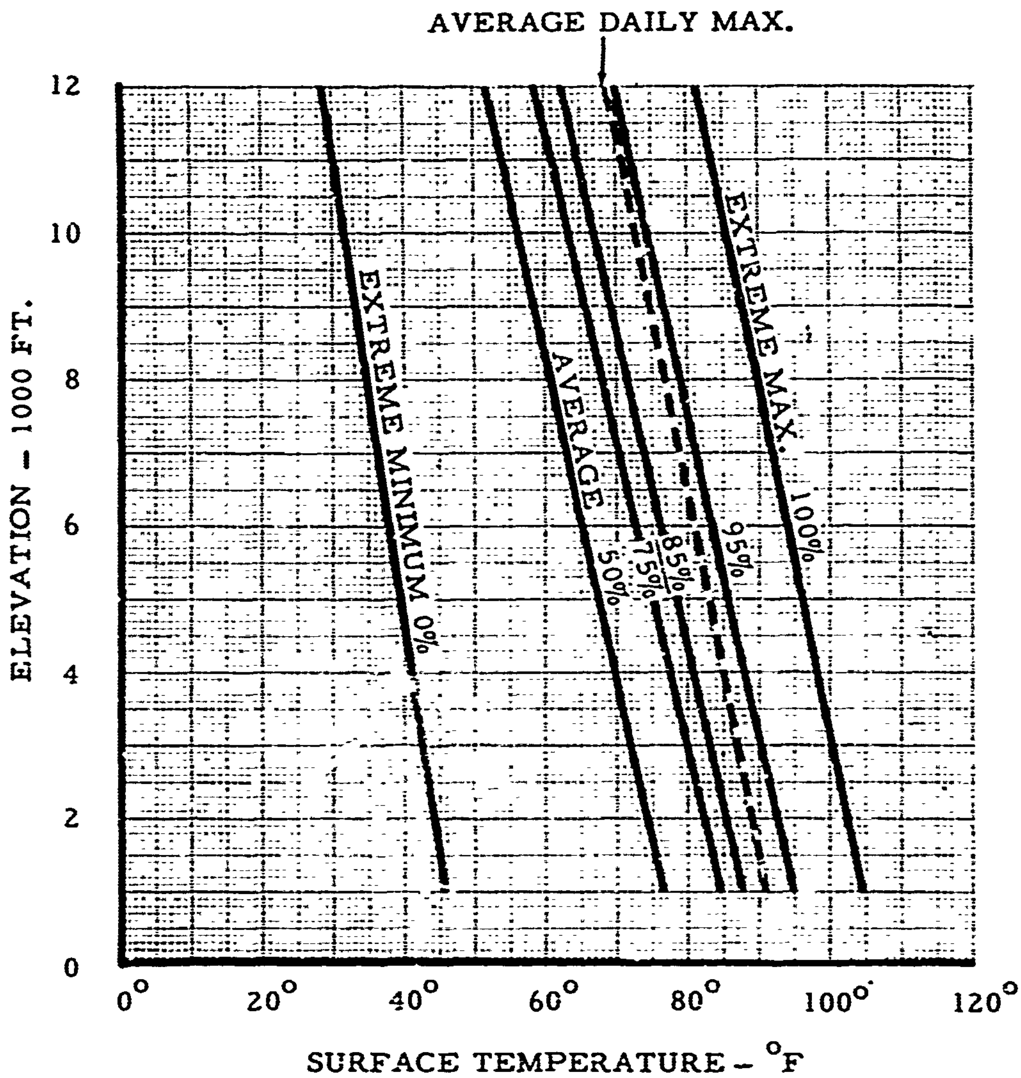


FIGURE 2

SURFACE TEMPERATURES FOR GIVEN PROBABILITIES OF NOT BEING EXCEEDED IN SOUTHWEST ASIA DURING THE HOTTEST MONTH

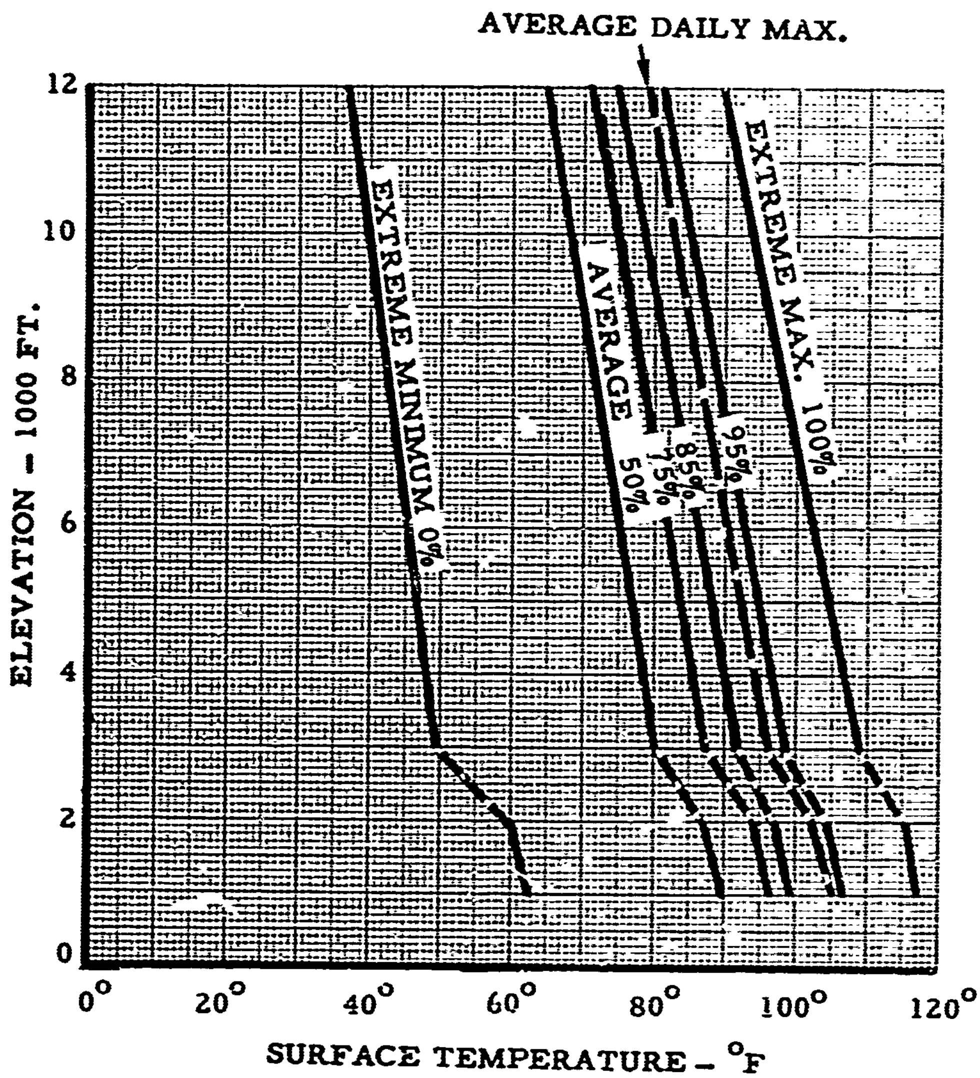


FIGURE 3

SURFACE TEMPERATURES FOR GIVEN PROBABILITIES OF NOT BEING EXCEEDED IN SOUTHEAST ASIA DURING THE HOTTEST MONTH

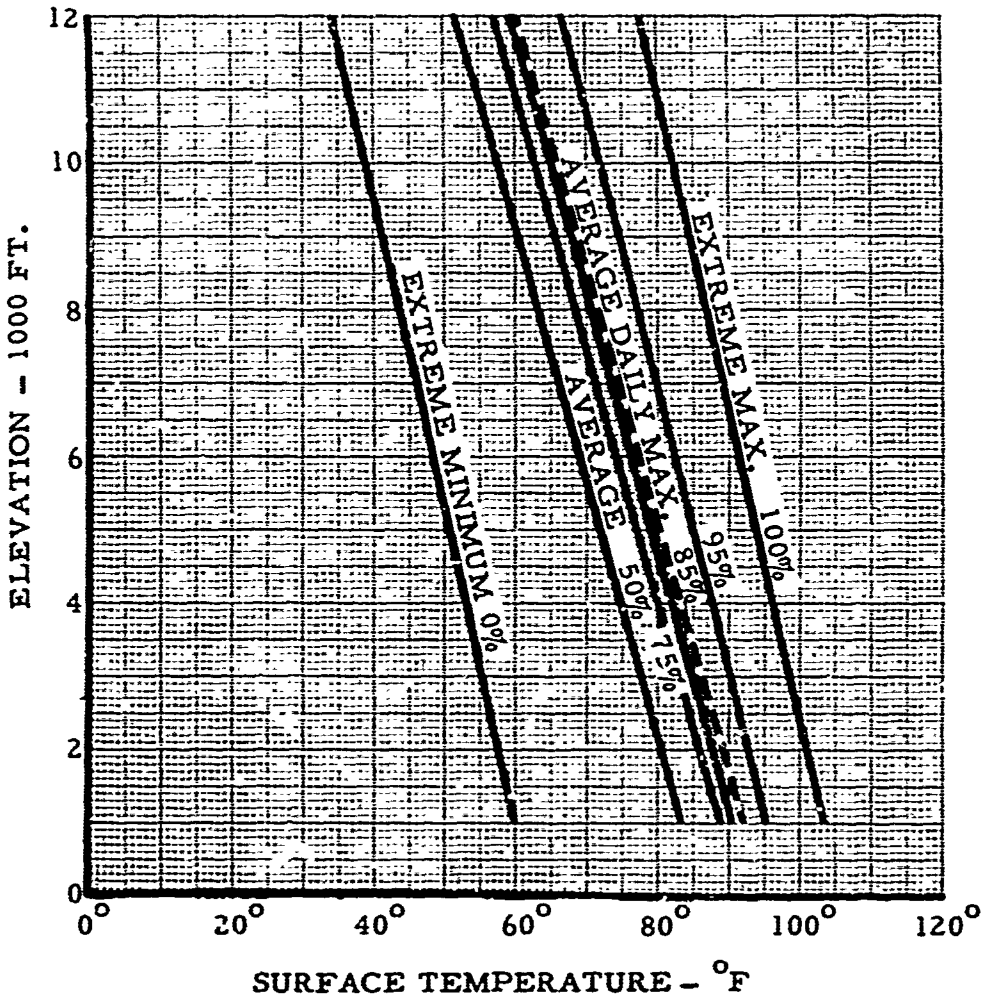


FIGURE 4

SURFACE TEMPERATURE FOR GIVEN PROBABILITIES
OF NOT BEING EXCEEDED IN IRAN-SAUDI ARABIA
DURING THE HOTTEST MONTH

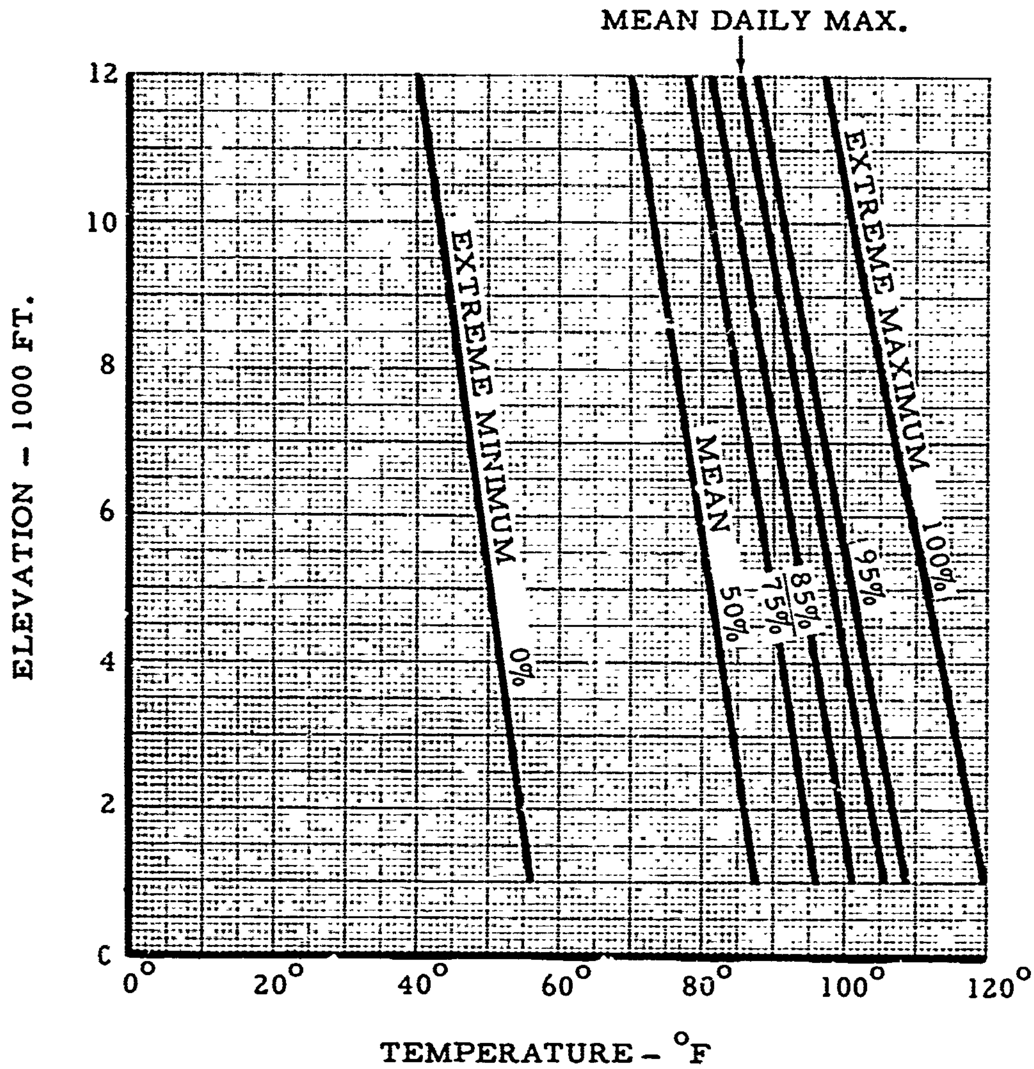


FIGURE 5

SURFACE TEMPERATURE FOR GIVEN PROBABILITIES OF NOT BEING EXCEEDED IN PAKISTAN – AFGHANISTAN DURING THE HOTTEST MONTH

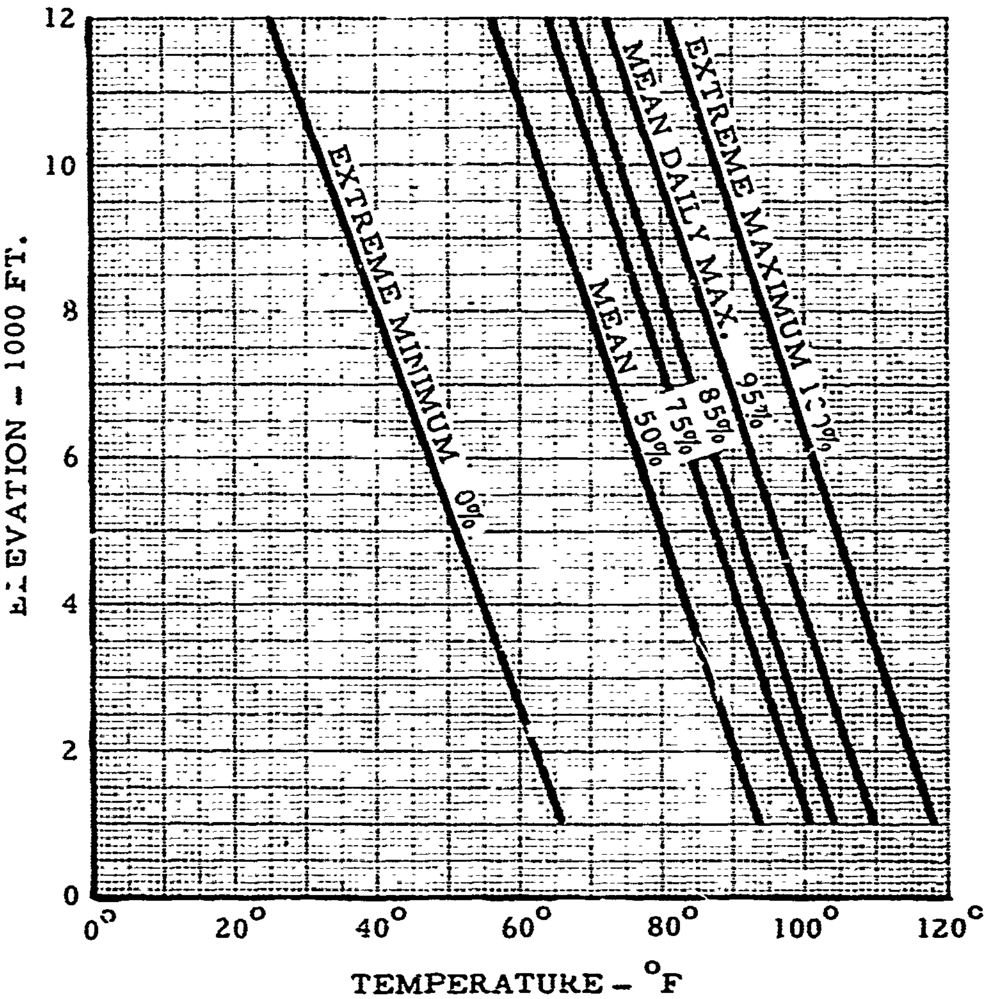


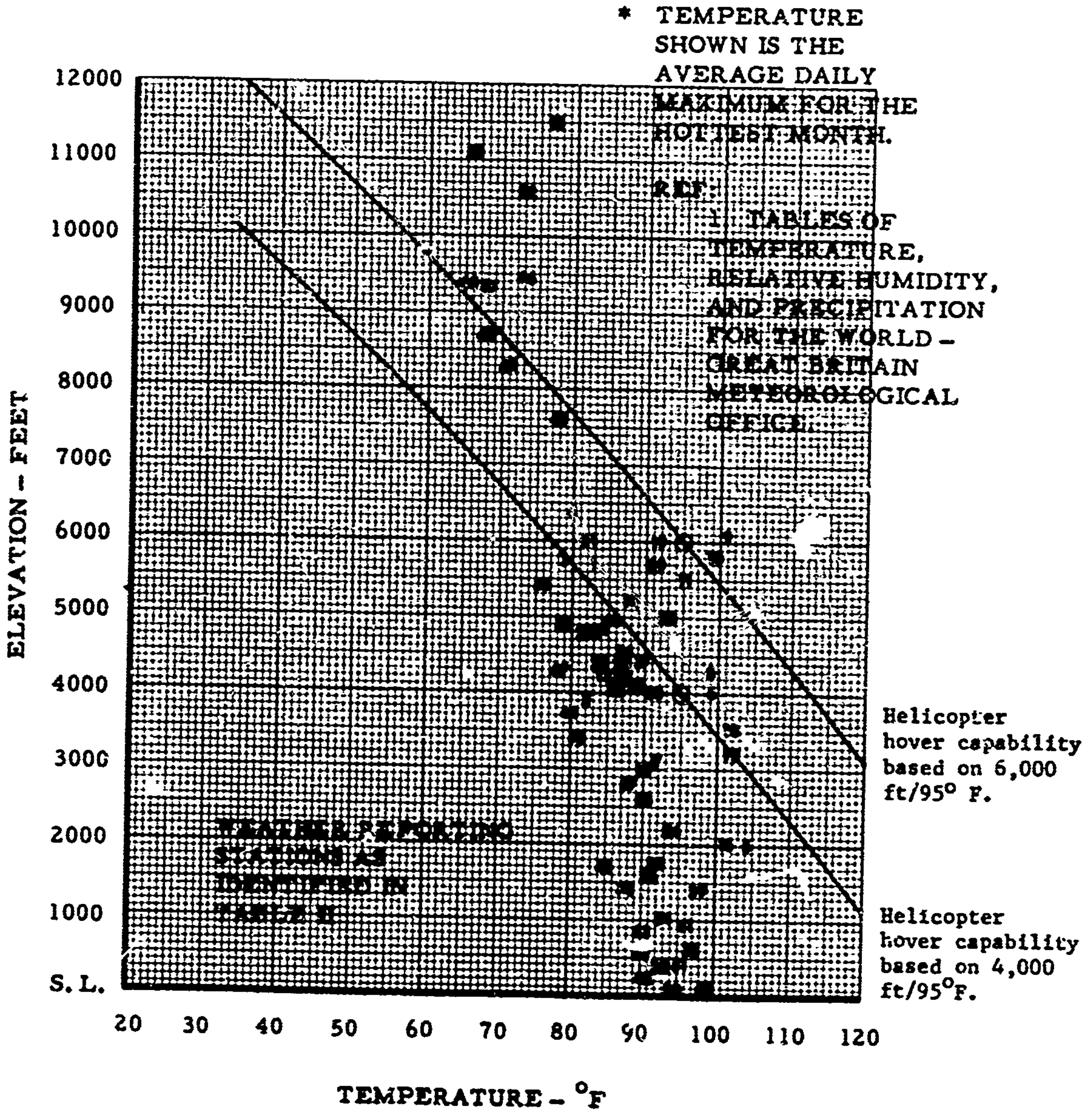
TABLE II

"TROUBLE SPOT" WEATHER REPORTING POINTS

	Country	Location	Elevation		Country	Location	Elevation
1	Turkey	Van	5682	33	Argentina	Mendoza	2625
2	Turkey	Sivas	3888	34	Argentina	Victorica	1024
3	Turkey	Kars	5741	35	Argentina	Santiago Del Estero	653
4	Turkey	Erzurum	6402	36	Bolivia	Conception	1607
5	Iran	Seistan	2000	37	Bolivia	Sucre	9344
6	Iran	Tehran	4002	38	Brazil	Caceres	387
7	Iran	Mesheo	3104	39	Brazil	Ibipetuba	1430
8	Iran	Kermanshah	4285	40	Chile	Potrerillos	9359
9	Iran	Kerman	6100	41	Chile	Santiago	1706
10	Iran	Isfahan	5817	42	Colombia	Andagoya	197
11	Pakistan	Quetta	5490	43	Colombia	Bogota	8678
12	Nepal	Katmandu	4388	44	Costa Rica	San Jose'	3760
13	Lebanon	Ksara	3018	45	Ecuador	Cuenca	8301
14	Kashmir	Srinagar	5205	46	Ecuador	Quito	9446
15	Kashmir	Leh	11503	47	Guatamala	Cobam	4285
16	Iraq	Rutba	2019	48	Guatamala	Guatamala City	4855
17	Arabia	Hail	3185	49	Mexico	Mexico City	7575
18	Afghanistan	Kandahar	3462	50	Mexico	Monterrey	1732
19	Afghanistan	Kabal	5955	51	Paraquay	Asuncion	456
20	South Africa	Victoria West	4124	52	Peru	Cusco	10581
21	South Africa	Sutherland	4777	53	Peru	Jauta	11113
22	South Africa	Mafeking	4173	54	Salvador	San Salvador	2238
23	South Africa	Kroonstad	4423	55	Venezuela	Caracas	3418
24	South Rhodesia	Salisbury	4831	56	Venezuela	Merida	5384
25	South Rhodesia	Bulawayo	4405	57	Venezuela	Santa Elena	2816
26	North Rhodesia	Solwezi	4542	58	South Vietnam	Dalat	4921
27	North Rhodesia	Kasempa	4439	59	South Vietnam	Saigon	36
28	Morrocco	Midelt	5003	60	South Vietnam	Tourane (Tien Sha)	509
29	Morrocco	Frherm	5741	61	Laos	Luang-Prabang	951
30	Congo	Elizabethville	4035	62	Cambodia	Kratie	79
31	Congo	Nioka	6234	63	North Vietnam	Lang Son	850
32	Argentina	Cordoba	1388				

FIGURE 6

TEMPERATURE*/ELEVATION CONDITIONS
FOR TYPICAL TROUBLE SPOT AREAS OF THE WORLD



(2) Figure 7 illustrates the variation of power loading with disc loading and rotor figure of merit.

(3) The power required to hover, defined in terms of rotor shaft horsepower per pound of aircraft gross weight, is the reciprocal of rotor power loading and is expressed in mathematical form as:

$$\frac{P}{W} = 0.0265 \frac{\sqrt{w}}{M} \left(\frac{1}{\sqrt{\sigma}}\right)\left(\frac{1}{1-\eta}\right)$$

A typical military helicopter has a rotor figure of merit, M = 0.75; a disc loading of w = 7 lb/ft^2; and is required to operate at 4,000 feet pressure altitude/ 95° F. (density altitude = 7,200 ft; $1/\sqrt{\sigma}$ = 1.114). Total power required is approximately 10 percent higher due to transmission losses (3 percent) and antitorque (tail rotor) power requirements (7 percent). 3/ Thus the actual power required for hover OGE at 4,000 feet/95° F. for the typical military helicopter discussed is:

$$\frac{P}{W} = \frac{0.0265 \times \sqrt{7} \times 1.114}{0.75 \times (1-0.10)}$$

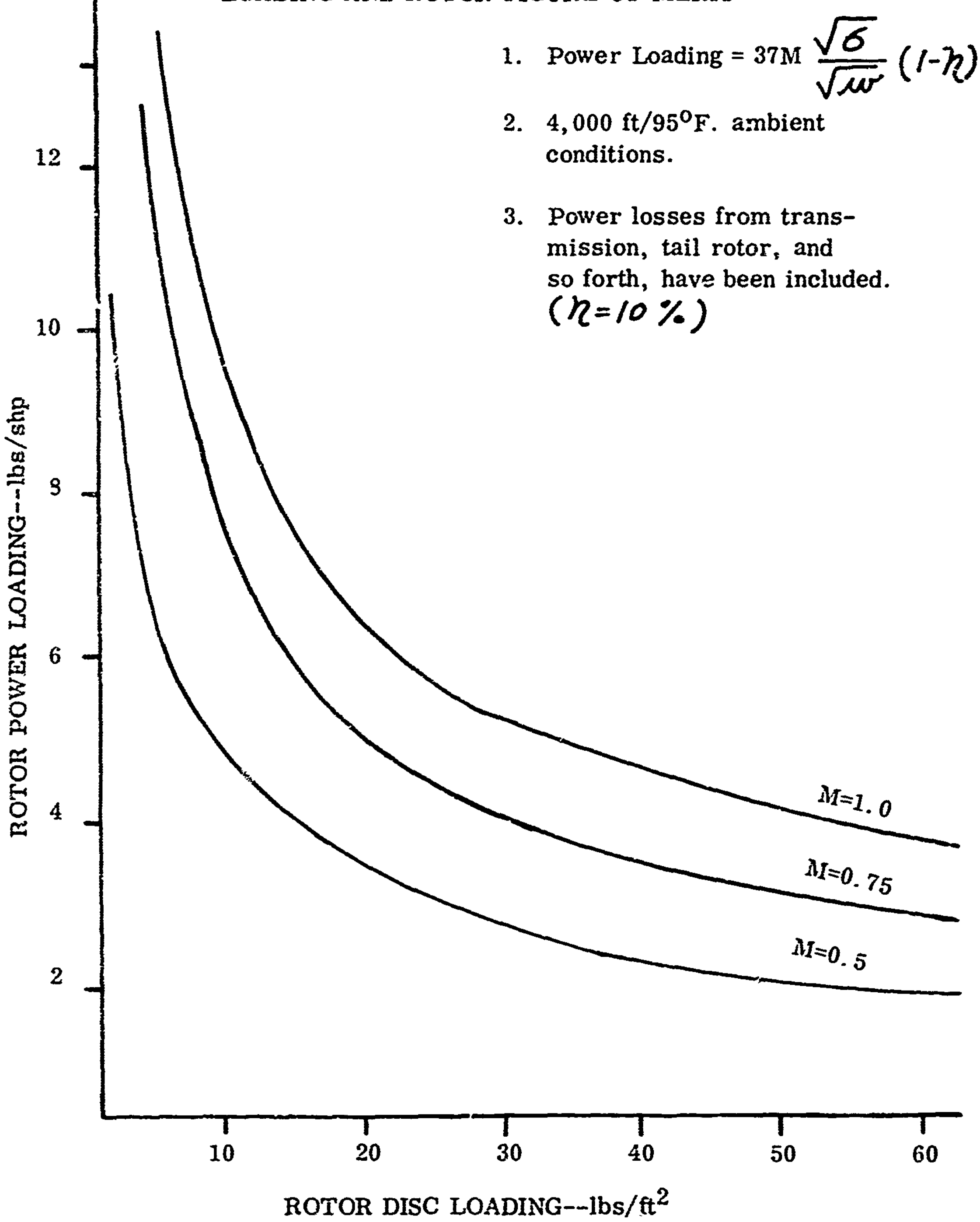
$$= \underline{0.12} \text{ shp/lb}$$

d. Climb Performance.

(1) Ground combat operations may be conducted in confined areas which impose distinct limitations on the mode of operation of the supporting helicopters. Access to these areas may be impeded by the location of trees, barricades, vehicles, shelters, powerlines, terrain irregularities, or other aircraft. These obstructions frequently necessitate vertical or near vertical takeoff and ascent to heights well above the influence of ground effect* before the helicopter can be accelerated through translational lift and achieve the desired climb airspeed. Furthermore, the location of enemy antiaircraft fire may require takeoff and landing approaches to be conducted "downwind" which increase the demands for

*The term "in ground effect" (IGE) refers to a special condition of improved performance encountered by helicopters when they are operated in close proximity to the ground. Rotor tip vortex strength is reduced and rotor downwash is flattened out by the surface which reduces rotor induced drag, permits rotor blade pitch angle to be reduced, and thus lessens the power required for flight. Ground effect is most pronounced at the surface, and extends upward with diminishing strength until at a height above the surface roughly equivalent to one rotor diameter in length all influence ceases.

FIGURE 7
VARIATION OF ROTOR POWER LOADING WITH ROTOR DISC LOADING AND ROTOR FIGURE OF MERIT



power and rotor lift. The problem is increased substantially when the supporting helicopters are operated in formation as is often necessitated for reasons of survival and timeliness. Turbulence is created by adjacent aircraft and is discussed in f below. Hot exhaust gases from the lead aircraft may be ingested by the engines of the following helicopters. Power losses experienced are 0.42 to 0.50 percent per $^{\circ}$F. of inlet air temperature increase for the current inventory turbine engine. The vertical climb performance should be sufficient to avoid delays in leaving the combat zone, minimize exposure time to enemy fire, and avoid delays in rejoining the formation. A rate of climb of 500 feet per minute is considered to be a minimum acceptable level for this purpose. (It will also serve to accommodate gusts as discussed in f below.) This requirement is established without benefit of data showing the influence of vertical climb performance on aircraft vulnerability to enemy ground fire. Additional vertical climb performance may be necessary to enhance survivability, especially if the aircraft possesses large vulnerable areas.

(2) The power allowance required to produce a vertical climb is derived in annex B. Figure 8 presents the variation of power required, expressed as a percent power increment above that required for hovering OGE versus rotor (thrust) disc loading for a vertical rate of climb of 500 fpm (8.33 fps) under 4,000 feet/95° F. ambient conditions. It can be seen that approximately 8 percent more horsepower above the required for hovering OGE must be provided to permit a helicopter with a 7 psf disc loading to climb vertically at 500 fpm under these ambient conditions.

(3) Figure 9 shows the power required by the Army's AH-56A compound helicopter to perform specified maneuvers as a function of pressure altitude when temperature is maintained at a constant 95° F. The intersection of the actual power available and power required for hover curves (point 1) shows that the hover OGE ceiling is approximately 4,800 feet at 95° F. From the intersection of the power available and power required for vertical climb curves (point 2), it can be seen that this particular aircraft should realize a 500 fpm vertical rate of climb at 4,000 feet/95° F. because of the design hover ceiling. The dash line shows power available if the vertical climb condition had been met using only 95 percent of available power. The intersection of this curve with the power-required-to-hover parameter shows that the equivalent hover ceiling would be increased to approximately 5,800 feet at 95° F.

e. Approach and Landing.

(1) The approach and landing phase of helicopter operations is often influenced by the same constraints as the takeoff phase previously discussed. When hostile fire is anticipated in the landing zone, fast flat approaches or near vertical approaches and landings are employed to minimize exposure time and

FIGURE 8

POWER MARGIN REQUIRED TO PROVIDE
500 Ft/Min VERTICAL CLIMB

1. Based upon momentum theory,
$$\frac{P_{i_c}}{P_{i_h}} = \frac{V_c \pm \sqrt{V_c^2 + \left(\frac{2}{\rho}\right)\left(\frac{T}{A}\right)}}{\sqrt{\left(\frac{2}{\rho}\right)\left(\frac{T}{A}\right)}}$$
2. Profile power is assumed to be 25% of the total hover power @ T/A=4 lbs/ft^2 and remains constant as disc loading varies.
3. Ambient conditions are 4,000 ft @ 95°F.

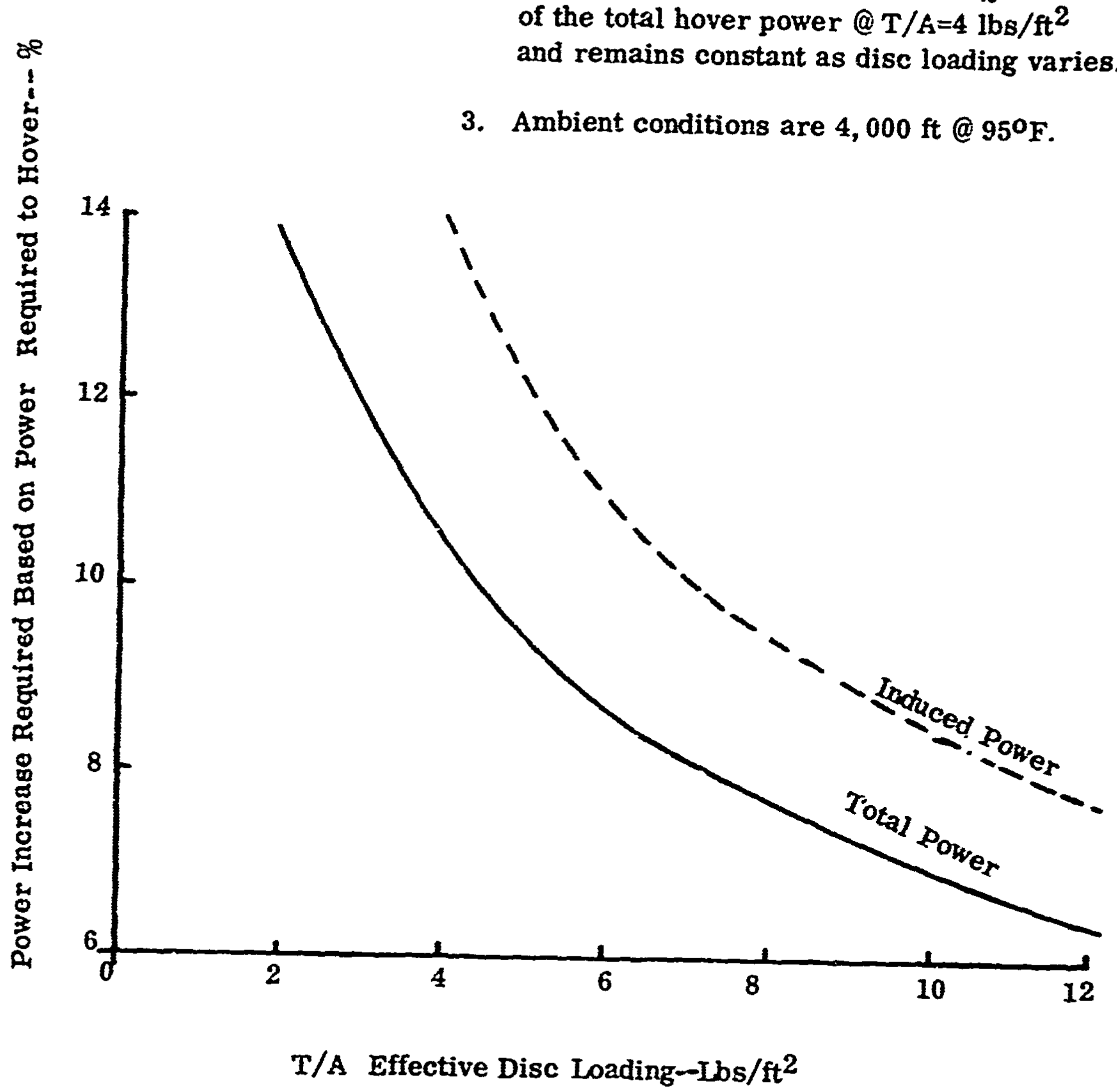
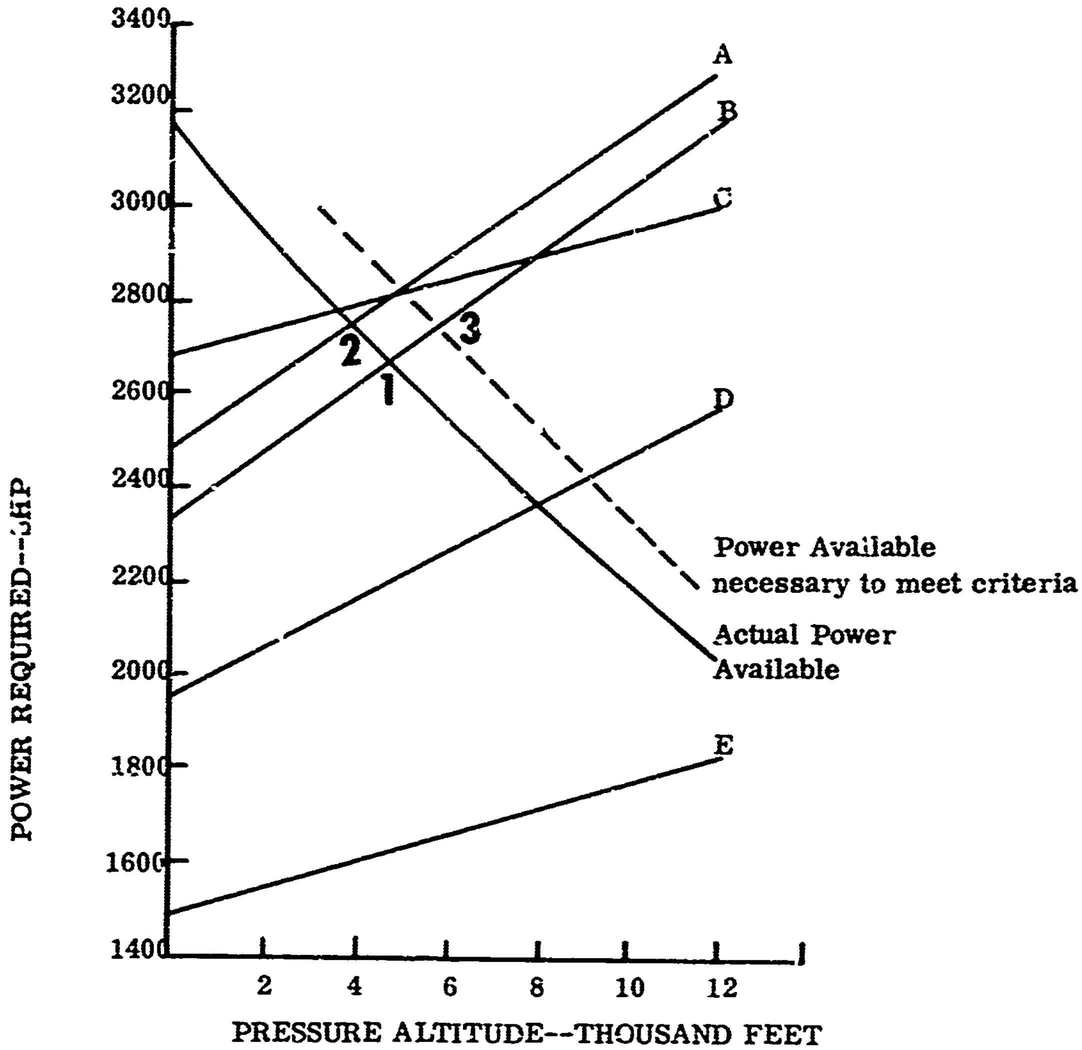


FIGURE 9

POWER REQUIRED AND AVAILABLE AH-56A COMPOUND HELICOPTER*



FLIGHT CONDITIONS--95°F. Constant Temperature.

A. Vertical climb @ 500 ft/min, zero wind.
B. Hover OGE, zero wind.
C. Stop descent from 90 kt, 12° glide slope, 15 kt tailwind, 100 feet above ground (OGE).
D. Stop descent from 90 kt, 12° glide slope, zero wind, 100 feet above ground (OGE).
E. Climb @ 90 kts, 500 ft/min, zero wind.

*Calculated data provided by the Lockheed California Company.

to avoid congestion in the area Additional power is required to arrest high sink speeds and zero out airspeed, and to compensate for the loss in lift created by the rotor wash of other helicopters. Furthermore, poor approach techniques, enemy actions, or clutter in the intended landing zone may preclude safe landing in that spot after the pilot has commenced his approach, thus necessitating a go-around. The analysis of power requirements to meet these situations is similar to that required for developing a vertical climb capability, except that ground cushion is of benefit in arresting the descent, thus the power required for this mode of operation is generally less than that required for a vertical climb. An exception to this occurs when a pinnacle landing is required and little or no favorable ground effect is available.

(2) Experience in Vietnam clearly shows the need for sufficient power to abort a steep approach into the landing zone (i.e., arrest the rate of descent and permit go-around if necessary). The technique employed with UH-1( ) aircraft is essentially a powered autorotation in which full power is applied and maintained from about 200 feet out, with collective pitch being pulled in the last 4-5 seconds to exchange rotor energy for additional power (rotor rpm generally decays beyond the "warning" limit) to cushion the impact. There is no excess lift available to stop the descent and go-around; the pilot merely hopes to control the aircraft's attitude at touchdown. Ground cushion also is used to reduce some of the lift required; thus, the point at which pitch is pulled is most critical (i.e., IGE with sufficient rotor rpm).

f. Gust Response.

(1) Turbulence, gusts, and wind components also have an adverse effect upon the various helicopter maneuvers discussed. Increased rotor lift must be available to counter downdrafts and to provide adequate control power to maintain aircraft attitude resulting from transient wind disturbances. A complete analysis of the gust response problem requires an understanding of the wind/gust phenomena; identification of the particular gust characteristics which significantly affect aircraft performance, stability, and control; the dynamic response characteristics of the specific aircraft model being considered; and the reingestion effects of gust components on certain VTOL aircraft configurations. 5/ The characteristics of gusts encountered at low altitudes are not fully understood at the present time, and are being studied in depth under USAF sponsorship. In the absence of any proven mathematical solution to this problem, an analysis based upon operational experience and mission requirements is suggested. Army helicopter missions are routinely performed in areas with known conditions of moderate turbulence. Severe turbulence also may be encountered inadvertently, particularly when flight operations are conducted in close proximity to significant terrain

irregularities such as tree lines immediately adjacent to the landing zone, cliff ridge lines, and mountains. Downdrafts on the order of 4-7 fps are encountered in moderate turbulence*, and may create a definite aircraft settling problem unless the descent is arrested by application of reserve power.

(2) The presence of other helicopters operating in the same general area creates a potential hazard due to the turbulence produced by the rotor downwash. The average downward velocities produced in this manner are directly proportional to the aircraft's rotor disc loading and inversely proportional to the aircraft forward speed and ambient air density. Surprisingly, downdrafts of over 8 fps may persist 1 to 2 minutes after the responsible aircraft has past. 6/ Subsequent passes through this same airmass can increase the strength of these downdrafts; thus, the condition presents a definite hazard to aircraft entering and departing the landing zone. Methods of minimizing the rotor wake hazard include maintaining a separation interval of from 1 to 1-1/2 minutes between aircraft, or operating successive aircraft either above or to the side of the preceding aircraft. Obviously, the timing of airmobile operations precludes such practices in the landing zone area.

(3) The power reserve, established in d above to provide a vertical climb capability of 500 fpm (8.3 fps), can be utilized to accommodate steady state downdrafts of this magnitude, and transient downdrafts of perhaps greater magnitude depending upon the gust characteristics, duration, and aircraft response properties. Thus, the use of the climb allowance simplifies the gust accommodation analysis considerably. The problem of recirculation may create a situation of "settling with power" from which escape would be difficult at best. Settling with power can be avoided during normal helicopter operations by observation of proper flight techniques. This should also be possible in gust environments.

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*Air Weather Service Manual 55-8, Volume I, 27 January 1967, defines moderate turbulence as "a turbulent condition where occupants require seat belts and occasionally are thrown against the belt. Unsecured objects in the aircraft move about." Severe turbulence is defined as "a turbulent condition where the aircraft momentarily may be out of control. Occupants are thrown violently against the belt and back into the seat. Objects not secured in the aircraft are tossed about." Resultant gust speeds are 20-35 fps and 35-50 fps, respectively. Information on the downward, vertical wind components of gust (i.e., downdraft magnitudes) encountered at low altitudes were provided by Mr. John Dempster of the Boeing-Witchita Division, and were based upon in-flight observations. Reported downdraft magnitudes for light, moderate, and severe turbulence were 0-4 fps, 4-7 fps, and 7-10 fps, respectively.

g. Effects of Ambient Conditions.

(1) Engine power output is reduced by increased ambient temperature, and by reduced ambient air density (a function of temperature and pressure altitude). Current turboshaft engines used in Army helicopters loose from 0.42 to 0.55 percent 7, 8, 9/ of maximum, military, and normal rated power per $^{\circ}$F. above standard (59° F.). These engines also loose approximately 3.5 percent of maximum, military and normal rated power per each 1,000 feet of pressure altitude above sea level. Thus, at 4,000 feet/95° F., 14 percent of the sea level rated power is lost because of altitude effects, and another 15-20 percent is lost because of increased ambient temperature. This is a total reduction of 29-34 percent below the sea level rated power. Turboshaft engines of the future may reduce the magnitude of these losses somewhat. The variation of power output with pressure altitude and ambient temperature for a typical turboshaft engine is illustrated by figure 10.

(2) The other influence of adverse ambient conditions on vertical performance is the reduction in aerodynamic efficiency of the rotor because of reduced air density. Lift produced by the rotor is a function of two variables--blade angle of attack and dynamic pressure at the blade. (Blade airfoil, blade area, and rotor speed are constant, and subsonic airflow over the blades is maintained.) Since the dynamic pressure experienced by the rotor blade is reduced proportionately to the reduction of air density, the blade angle of attack (pitch) must be increased to increase the lift coefficient and thus maintain lift. This is a design consideration which the manufacturer can readily accommodate through selection of the rotor blade airfoil and blade area during the initial design. It is normally of less concern than the engine power variations.

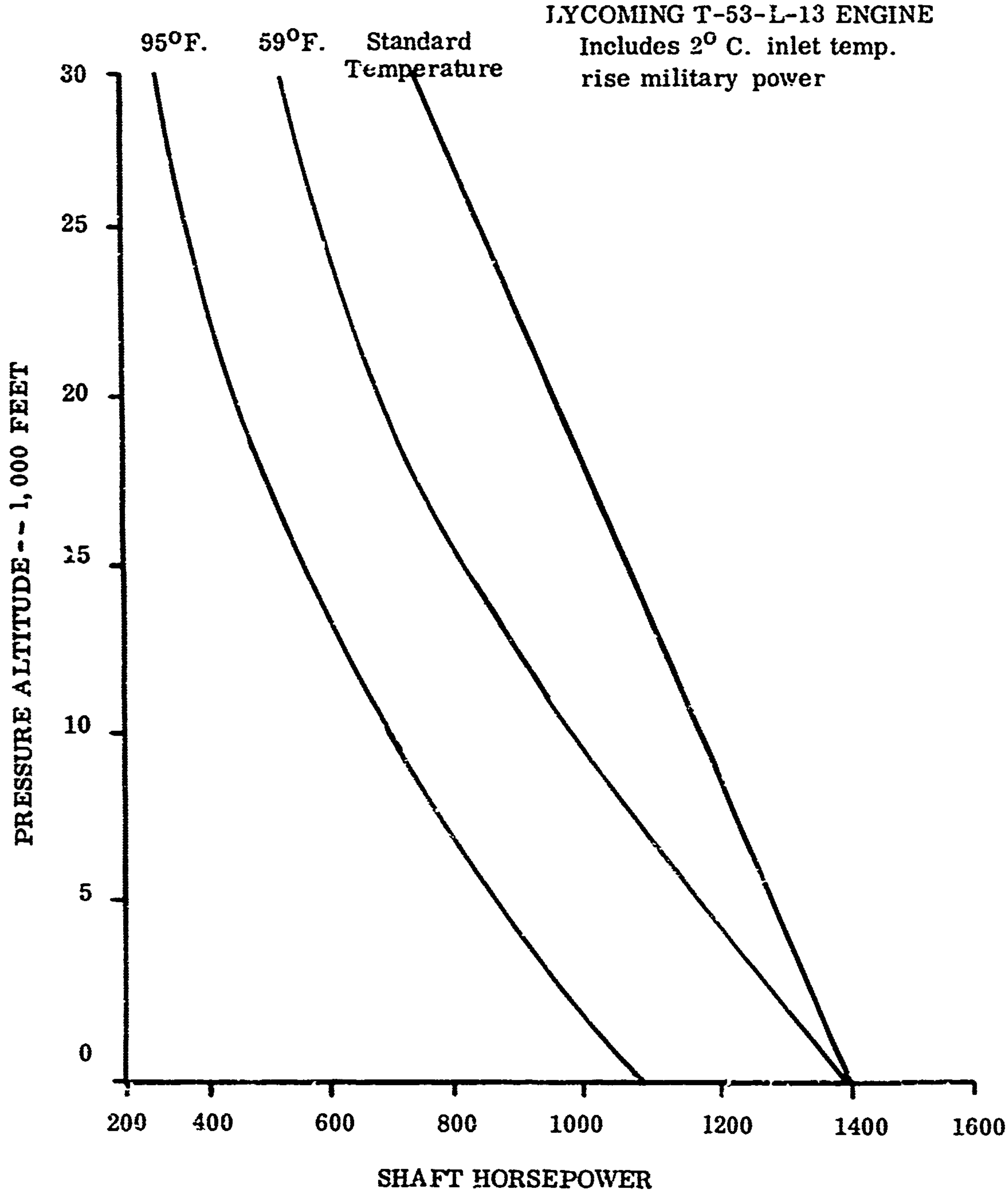
h. Effects of Airframe/Rotor Deterioration.

(1) Erosion of helicopter main rotor and tail rotor blades is a serious problem when helicopters are operated from unprepared surfaces. Army helicopters must operate for prolonged periods of time in dusty/sandy areas, and thus encounter serious erosion problems.

(2) Rotor blade aerodynamic efficiency, a function of blade airfoil section lift to drag ratio, is reduced by erosion. Additional blade collective pitch application is then required to maintain the necessary rotor lift. This increases the profile drag (blade form drag) of the rotor. Furthermore, the outer portions of the rotor blades experience the most severe erosion damage because the blade-particle impact velocities are high (blade element velocity increases in direct proportion to its distance from the rotor hub), and because airborne

FIGURE 10

VARIATION OF ENGINE POWER WITH PRESSURE ALTITUDE AND AMBIENT TEMPERATURE



particle concentration is higher at the tip (rotor downwash velocity which creates the dust cloud is higher at the tip plane than inboard). 10/ As a result of these effects, power must be increased to continue development of the required lift.

(3) Rotor blade erosion becomes a serious problem when aircraft are operated in sandy or dusty areas. Serious erosion has been experienced by Army helicopters operating in Vietnam, and rotor blade protection means have been quickly developed to extend blade life. The unprotected UH-1 blades last approximately 300 hours during dry-season operations. When protected, blade life may be extended by a factor of 2-3. Rotor blade erosion experienced by the CH-47A Chinook has not created significant increases in the power required for hover (estimated increase is 1 percent or less), and blade replacements for erosion damage have generally been necessitated by mass balance problems. It is assumed that the mass balance problem occurs before the erosion seriously alters the rotor blade aerodynamic characteristics.

i. Effects of Engine Erosion.

(1) The effects of dust/sand ingestion on turbine engine performance are similar to the effect of rotor blade erosion. The first stage of the engine compressor generally experiences the most severe erosion both in compressor/stator blade airfoil deformation and in increased compressor blade tip to compressor case clearance. Both forms of erosion degrade compressor efficiency, and generally result in reduced engine power available and increased specific fuel consumption (SFC).

(2) The rate of accumulation of erosion damage and, to some extent, the severity of damage can be reduced by use of particle separators (generally of the centrifugal/inertial type) and/or filters located in the engine inlet ducts. However, these devices reduce duct recovery efficiency, and thus create moderate power losses (approximately 2 percent of rated power) and increased aircraft empty weight (100-200 lb for current utility and medium helicopters).

(3) Experience with the T53-L-9/11 engines installed in UH-1 helicopters, without protective devices, shows an average deterioration because of erosion of 9.1 percent at the end of the time between overhauls (TBO) period (1200 hours). The engines considered were all high time engines. Since many of the UH-1 helicopters operated in Vietnam required engine replacement because of erosion after only a few hundred hours of operation, the sample "high time" engines probably experienced only moderately dusty operating conditions. However, the rate of erosion damage accumulation is of little significance to this study (assuming that engine rejection from erosion occurs before the TBO period

is achieved); it is the magnitude of power lost before the engine is changed that is of significance. It is significant that incorporation of filters in the UH-1( ) inlet reduces the rate of erosion damage, permitting many engines to achieve the specified TBO period.

(4) Experience with the T55 engines installed in the CH-47A has been more favorable, averaging only a 4 percent power loss at time of removal. However, the aircraft on which this data was accumulated had not received the same exposure to dust and sand, on the average, as had the UH-1. (Much of the CH-47A total flight time has been in CONUS; whereas, the UH-1 have extensive experience in Vietnam.)

j. Effects of Engine Maintenance. There are two other operational problems which have reduced installed engine power, but which do not show up in the engine erosion tests discussed above. These factors are as follows:

(1) Accumulation of dirt in the engine inlet ducts and the engine itself, but which has not yet caused engine erosion. Helicopters operating in Vietnam have experienced marked power losses from this cause, and it is necessary to "wash" the T55 engines in the CH-47 every 10-12 hours of operation to clear this dirt.

(2) Engines installed in Army helicopters are not always retrimmed in the field to account for different ambient temperatures and pressures. It is not possible to assess the magnitude of power lost because of this; but, it is worth noting that this problem does exist in certain situations.

k. Engine Installation Losses. It is generally recognized that when installed in an aircraft of any type, an engine experiences certain "installation" losses, and thus it produces less than specification horsepower. The aircraft manufacturer makes allowances for many of these losses during design; however, not all are anticipated at this stage. Engine inlet air temperature is increased a minimum of 3-4^{0} F. merely as it passes through the intake. Heat is added by skin friction and by proximity to the hot engine itself, to gearboxes, and to other heat sources. When duct screens or other engine air filtering means are added to prevent engine erosion from sand and dust, the engine inlet temperature rise may be doubled. This problem can be accommodated by the designer if the aircraft operational requirements are fully understood and engine protection is specified in the QMR and applied to the procurement specifications. Thus, this condition should be accommodated in the Army's future designs, and need not affect the hover criteria established by this study.

1. Aircraft Weight Growth.

(1) It is a well known fact that as successive blocks of production of a particular aircraft are delivered, and as these aircraft are operated, maintained, and repaired in service, aircraft gross weight increases. This is due to three principle sources, none of which are fully allowed for in the original design. These main sources of weight are--

(a) Design improvements in subsequent production models to correct deficiencies, improve capabilities or component strength, and adopt newly available subsystems which may or may not have been envisioned during the original design.

(b) In-service weight acquired in the form of structural repairs (patches and doublers), accumulation of dirt, grease, and fluids; and addition of mission equipment desired by the various operational units to meet their specific problem areas (e.g., extra oil, water, rations, armor plating, weapons, and ammunition).

(c) Expansion of the aircraft's mission requirements to perform secondary tasks not originally assigned or envisioned. The use of the UH-1 (originally designed as an aeromedical evacuation aircraft) as a squad carrier (UH-1D) and gunship (UH-1B/C) at substantially higher mission gross weights is an extreme example of this mission growth. Unfortunately, these forms of growth occur after the rotor and airframe have been put into production; thus, the rotor disc loading is increased proportionate to this growth, and the power loading factor is degraded.

(2) Typical weight growth of production Army helicopters can be seen in the following tabulations of CH-47A and UH-1( ) aircraft:

CH-47A

Production model year	Representative aircraft unit no.	Basic empty weight (lb)
FY 60	B-7	17,117
FY 61	B-12	17,165
FY 62	B-30	17,132
FY 63	B-54	17,495
FY 63	B-76	17,748
FY 64	B-78	17,759
FY 65	B-138	18,027
FY 66	B-198	18,037
FY 66	B-256	18,057

Weight growth of 940 pounds represents an increase of:

$\frac{940}{17,117} \times 100\% = \underline{\underline{5.5\%}}$ or $\underline{\underline{0.9\%}}$ per year.

UH-1B/C

Production model year		Basic empty weight (lb)
FY 60	UH-1B	4,410
FY 61		4,440
FY 62		4,460
FY 63		4,520
FY 64		4,530
FY 64	UH-1C	4,820
FY 65		4,840
FY 66		5,100

Weight growth of 590 pounds represents an increase of:

$\frac{590}{4,410} \times 100\% = \underline{\underline{13.3\%}}$ or $\underline{\underline{2.2\%}}$ per year.

UH-1D

Production model year	Basic empty weight (lb)
FY 62	4,700
FY 63	4,730
FY 64	4,800
FY 65	4,830
FY 66	5,050

Weight growth of 350 pounds represents an increase of:

$\frac{350}{4,700}$ x 100% = 7.4% or 1.8% per year.

(3) Since much of the weight growth is caused by the addition of specific items, the percentage increase of a given item should appear to be greater in the smaller aircraft (UH-1), thus explaining the greater percent weight growth of the UH-1. Also, the UH-1 series has had substantially greater utilization in Vietnam, and thus has had more basis for change than has the recently introduced CH-47. Typical of the empty weight growth from the initial production aircraft to the better defined aircraft configurations of subsequent procurement is 15 percent of the first production aircraft empty weight. This is derived by extrapolating the observed weight growths of the CH-47A, UH-1B/C, and UH-1D to the end of their planned 10-year service life. Since the Army generally retains such aircraft well beyond this design service life, the 10-year basis is considered to be conservative. Furthermore, it does not include the weight increases achieved because of in-service repairs, mission equipment changes, and mission expansion.

(4) A 15 percent increase in empty gross weight is not necessarily indicative of the mission gross weight which is influenced by the additional considerations of payload and mission equipment changes. For illustrative purposes, a 10 percent increase in gross weight has been assumed (i.e., very little change in mission equipment and payload compared with the 15 percent empty weight growth). The additional power required to accommodate this 10 percent gross weight increase can be found by examination of the power factor equation developed in annex A--

$$\frac{P}{W} = 0.0265 \; \frac{\sqrt{w}}{M} \left(\frac{1}{\sqrt{\sigma}}\right)\left(\frac{1}{1-\eta}\right)$$

by substituting $W/\pi R^2$ for w, and rearranging terms,

$$P = \frac{0.0265}{M\sqrt{\pi R^2}} \left(\frac{1}{\sqrt{\sigma}}\right)\left(\frac{1}{1-\eta}\right) W^{3/2}$$

A ratio of power required at the over gross weight condition (P') to power required at the design gross weight (P) can be formed, permitting cancellation of all constant terms. Thus,

$$\frac{P'}{P} = \left(\frac{W'}{W}\right)^{3/2}$$

When operating at a 10 percent over gross weight condition ($W'/W = 1.10$),

$$\frac{Pi'}{Pi} = (1.10)^{3/2}$$
$$= 1.15$$

Thus, a power increase of approximately 15 percent is required to accommodate a 10 percent gross weight increase.

(5) It is essential that both the aircraft manufacturer and developing activity consider growth potential in the initial design and selection of engines, transmissions, components, and airframe structure and aerodynamics to accommodate these periodic weight increases, and then maintain strict weight control over the successive blocks of production aircraft.

m. Pilot Factors. Aircraft in service seldom achieve the level of performance intended. The performance requirements specified as essential to completion of the mission in the QMR and subsequent production contracts may have been successfully demonstrated by the factory pilots early in the aircraft's development program; however, the problems of weight growth, adverse ambient conditions, airframe and engine deterioration, and maintenance problems reduce the service performance as discussed previously. One other factor which reduces the performance achieved is the ability of the pilot. The experienced factory test pilot can extract the maximum performance available from an aircraft because of his intimate knowledge of the aircraft, polished techniques, and ability to devote his undivided attention to maintaining the optimum flight profile.

The service pilot, however, is usually less proficient in the type aircraft, must concern himself with a variety of problems pertaining to his mission (e.g., navigation, formation, communications, coordination with other aircraft and ground units, weapons firing), and is often distracted by enemy antiaircraft fire, excessive air traffic, and the actions of his crewmembers. Although no quantitative allowance can be established to counter these losses, it is considered important that the problem be recognized.

n. Accident Experience.

(1) The preceding discussion was concerned with specific performance capabilities which are considered essential for satisfactory mission accomplishment. It is well known, however, that the majority of the Army's tactical helicopters is incapable of achieving the level of performance described when configured and equipped for combat operations in Vietnam. Since the Army must utilize whatever capability it has, man and machine are taxed to the limit in order to perform essential combat missions. Often the limits of one or the other are exceeded, and an accident results.

(2) The UH-1 series of helicopters has evolved from a 6,600-pound gross weight aeromedical evacuation aircraft into a 9,500-pound gunship (UH-1B and UH-1C) and a 9,500-pound troop transport (UH-1D). These aircraft are unable to hover OGE at these gross weights even at standard sea level conditions (59° F.), and are approximately 2,000 pounds above the maximum gross weight at which they can be hovered OGE at 4,000 feet/95° F. Thus, to permit operation under the environment encountered in Vietnam, a special set of operating techniques were employed. Running takeoffs in which the helicopter is skidded and bounced across the ground until translational lift has been achieved and flight is possible are often employed as the only means of achieving flight. Many aircraft are destroyed and crews injured or killed when takeoff is not achieved or when there is insufficient power available to clear trees and other obstructions. Once airborne and in formation, problems of inadequate engine power and poor aerodynamic control power (slow response) make formation flight difficult. The trailing helicopters are exposed to the downdrafts created by the preceding helicopters (discussed in f above) and have difficulty maintaining formation position or altitude. As the landing zone (LZ) is approached, the formation tightens to permit rapid entry and departure to and from the LZ. Here an "accordian effect" may be experienced. As aircraft attempt to close formation, they may have insufficient power to decelerate and loose altitude to avoid running into the aircraft ahead or use so much collective application to avoid contact that rotor rpm is lost and the aircraft cannot maintain its position. During descent, there may be insufficient power available to permit a go-around if the LZ is too

congested, and the pilot uses up all of his engine power and rotor RPM to arrest his descent and control the aircraft's attitude at impact. The accident summaries reflect the results of such practices! A summary of accidents occurring in all types of Army aircraft operated in Vietnam during the period 1 January 1966 through 31 December 1966 is presented below: 11/

USARV
COST BY TYPE OF ACCIDENT
AND PERCENTAGE OF TOTAL
1 JANUARY 1966 THROUGH 31 DECEMBER 1966

CAUSE FACTOR	NUMBER	PERCENT	*TOTAL COST
Loss of rpm, overgross, high density altitude	71	17.3	$12,361,633.61
Aircraft struck obstacle	56	13.5	5,024,551.85
Engine failure	35	8.5	4,734,785.19
Materiel failure	34	8.3	7,096,011.71
Faulty autorotative technique	30	7.3	2,437,211.98
Lost directional control	22	5.3	1,316,842.60
Engine failure with suitable area available	21	5.1	2,174,885.75
Weather	20	4.8	7,830,028.00
Hard landing	19	4.6	1,261,069.13
Meshed rotor blades	16	3.9	3,001,367.55
Landing short or long	16	3.9	2,919,111.91
Maintenance error	11	2.8	2,067,152.35
Foreign object struck tail rotor	10	2.4	3,363,397.04

See footnote at end of list, page 33

CAUSE FACTOR	NUMBER	PERCENT	*TOTAL COST
Stalled out	8	2.0	1,024,103.00
Wire strike	7	1.7	696,656.28
Flew into the ground	6	1.5	1,464,796.01
Flew into water	4	1.1	961,937.00
Midair collision	4	1.1	2,375,560.94
Unknown	4	1.1	1,515,294.00
Faulty slope technique	4	1.1	150,026.00
Faulty sling technique	4	1.1	980,772.28
Fuel exhaustion	3	0.7	265,639.99
Damage by propwash or rotor downwash	2	0.5	20,250.00
Ground collision	2	0.5	127,800.00
Uncontrollable slingload	1	0.2	1,800,015.00
Premature gear retraction	1	0.2	210,000.00
TOTAL	411	100.0	$67,231,772.17

*Total cost includes parts and man-hours expended.

(3) Notice that the "loss of rpm, overgross, high density altitude" category is responsible for 71 aircraft accidents or 17.3 percent of all Army aircraft accidents in Vietnam. (Percentages are misleading since fixed wing accidents are included resulting in the apparently low percentage.) Furthermore, several of the accidents attributed to aircraft struck obstacle, hard landing, landing short or long, wire strike, flew into ground, flew into water, midair collision, unknown, and faulty slope technique may have been caused by inadequate vertical performance capabilities of the helicopter. Possibly even

more significant is the fact that these deficiencies increase aircraft vulnerability by lengthening exposure time to enemy ground fire and may contribute to the combat loss rate. Such losses are not included as accidents in the totals on the above chart.

o. Engine Power Reserves.

(1) The preceding discussion has established operational requirements for definite reserve power allowances in military helicopter designs However, design requirements of this nature usually entail compromise in other areas which may appear as increased size, weight, cost, or complexity.* Heretofore, increased engine power in helicopters has resulted in weight increments of 0.2 lb/shp (uninstalled) plus 2 pounds of aircraft gross weight per each additional pound of fuel carried (helicopters only, other configurations experience greater weight increments). Procurement cost is approximately $40 for each additional shaft horsepower. The increased fuel capacity is generally required because of the tendency to utilize the extra power, and because cruise and other low-power flight conditions are conducted at reduced power settings which result in increased specific fuel consumptions (SFC)** in contemporary engines.

(2) Problems of increased SFC at reduced power settings, however, may not persist in the next generation of turboshaft engines. The U. S. Army Aviation Materiel Laboratories solicited industry proposals for a demonstrator engine program on 17 February 1967 under RFQ DAAJ02-67-Q-0039, and contracts have been awarded to General Electric and Pratt & Whitney for the construction and testing of prototype engines. The purpose of this program is to demonstrate a "breakthrough" in the technology of medium (1,500 shp) size turbine engines. Engine weight reduction of 40 percent, cruise SFC reductions of 25-30 percent, maximum power SFC reductions of 20-25 percent, and minimum power loss due to high elevations and temperatures (up to 6,000 feet/95^{o} F.) are the program objectives.

(3) Advanced engine technology forecasts show that a nearly constant SFC may be achieved over the range of cruise to maximum power settings, and advanced engine designs employing regenerative cycle techniques should provide optimum (reduced) SFC in the cruise power settings. This would eliminate the cruise inefficiencies previously associated with extra power, and may actually tend to cancel the remaining penalties of installation weight and additional

*Cost and weight factors are based on current practice, and were provided by the U. S. Army Aviation Materiel Laboratories and the Lockheed California Company.

**Specific fuel consumption (SFC) is engine fuel flow per shp per hour. Thus, inefficient operation is accompanied by increased SFC.

procurement cost. Figure 11 shows the relationship of SFC to power setting of the engines discussed. 12/

(4) Allowances for adverse ambient temperatures and densities may be made without entailing the weight and cost of stronger aircraft dynamic components by "flat rating" engine output. This technique involves the selection of an engine which provides sufficient power to permit operation under the most unfavorable ambient conditions selected for design purposes. A power limit equal to that required for operation at this most adverse ambient condition is then imposed and observed under all situations. This permits use of lighter dynamic components and structure throughout the aircraft than would be required if the engine's actual low altitude output had to be accommodated. Other advantages of the flat rating approach include long engine life because the engine is operated below maximum output most of the time, and a power reserve at all but the upper ambient limits to accommodate some of the problems previously discussed. Even the poor SFC obtained at partial power operations in the current engines may be reversed. Flat rating also simplifies mission planning in the field by permitting lift of the design payload (a constant) at all ambient conditions up to and including the selected design altitude/temperature.

(5) The influence of power reserves and power losses on hover performance was examined to answer the inevitable question--"What does all of this mean in terms of hover ceiling?" The variation of the hover OGE ceiling (at a constant 95° F. ambient temperature) with engine power settings above and below that required to hover OGE at the design baseline conditions of 4,000 feet pressure altitude and 95° F. temperature was developed in the following manner:

The power to weight ratio required for hovering OGE at the design ambient baseline was derived in Annex A as--

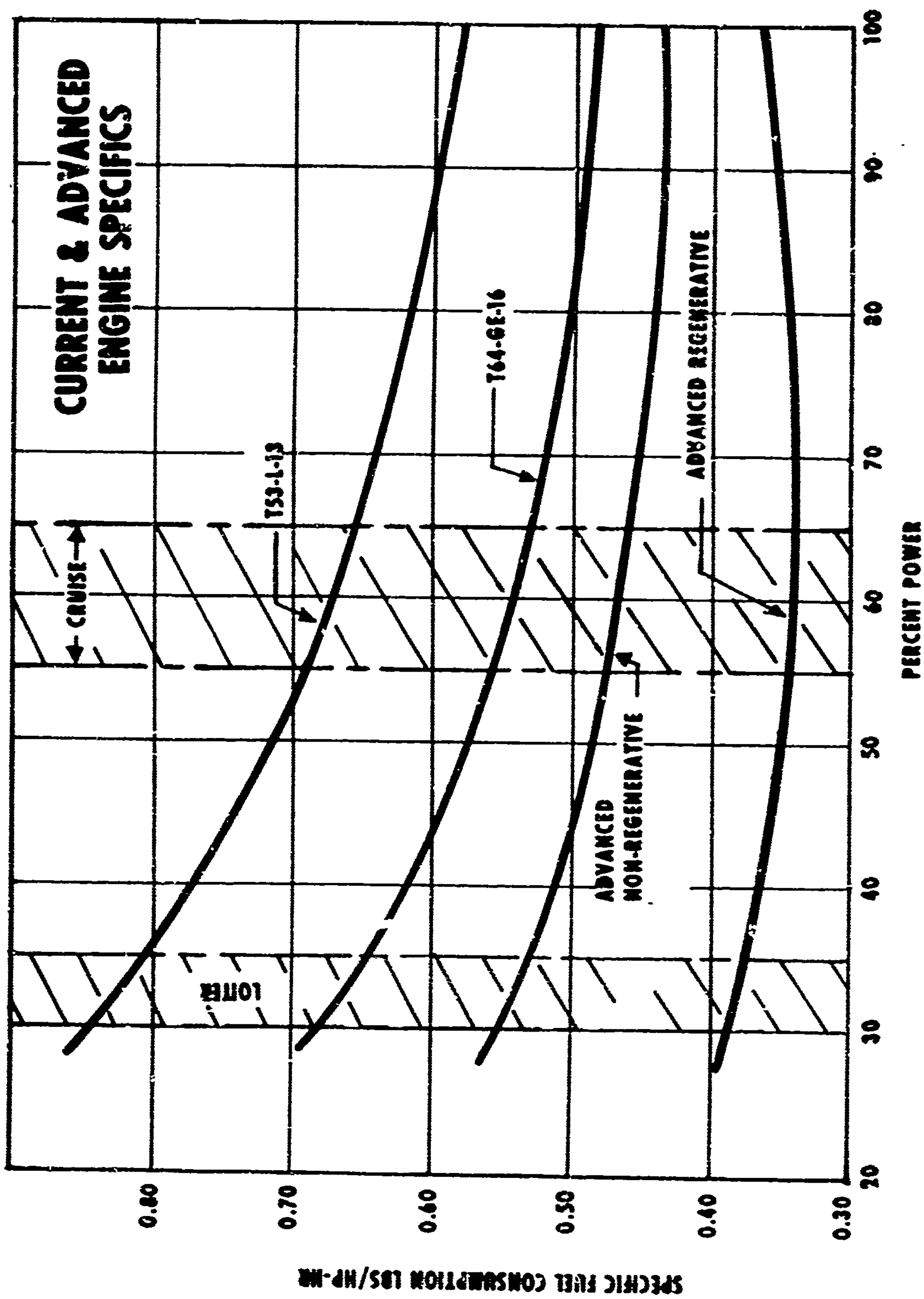
$$P/W = 0.0265 \frac{\sqrt{w}}{M} \left(\frac{1}{\sqrt{\sigma}}\right)\left(\frac{1}{1-\eta}\right)$$

At some "off design" power availability level (P'), the power to weight expression becomes--

$$P'/W = 0.0265 \frac{\sqrt{w}}{M} \left(\frac{1}{\sqrt{\sigma}}\right)'\left(\frac{1}{1-\eta}\right)$$

(The prime (') denotes the new condition.)

FIGURE 11


CURRENT & ADVANCED ENGINE SPECIFICS
T53-L-13
T64-GE-16
ADVANCED REGENERATIVE
ADVANCED NON-REGENERATIVE
CRUISE
LOITER
20
30
40
50
60
70
80
90
100
PERCENT POWER
0.30
0.40
0.50
0.60
0.70
0.80
SPECIFIC FUEL CONSUMPTION LBS/HP-HR

By setting a ratio of the off-design power (P') expression to the design power (P) equation, and cancelling all constants (0.0265, $\mathcal{M}$, M, and W), the relationship of off-design to design power becomes--

$$\frac{P'}{P} = \frac{(1/\sqrt{\sigma})'}{(1/\sqrt{\sigma})}$$

solving for the density term, we find

$$(1/\sqrt{\sigma})' = (1/\sqrt{\sigma})\frac{P'}{P}$$

This equation can be plotted in terms of pressure altitude and power variations (figure 12) by converting the $(1/\sqrt{\sigma})'$ into pressure altitude values, holding temperature constant at 95° F.

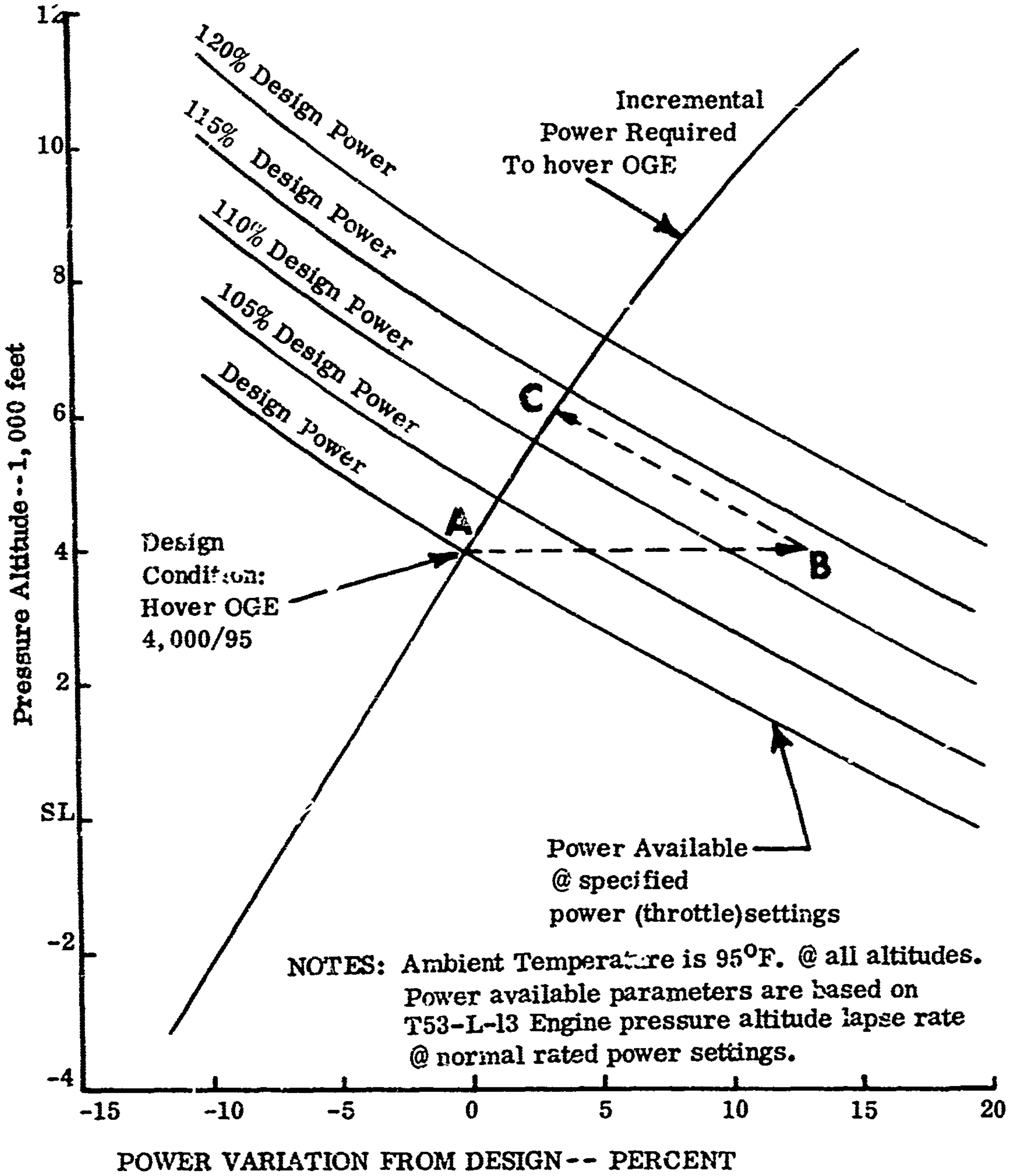
Now by superimposing parameters of engine power available at specified throttle (power) settings (showing typical engine power output variations at a given throttle setting due to changes in pressure altitude), we can obtain the equivalent hover ceiling at "off design" power conditions. This occurs at the intersection of the power required to hover parameter with the selected power available parameter. These effects are illustrated by the following example:

The typical helicopter discussed in paragraph 4c(3) had a rotor disc loading of 7 psf. Figure 8 shows that a power increment of 8 percent above that required for hovering at 4,000 feet/95° F. is needed to satisfy the requirement for a 500 feet/minute vertical climb at these conditions. The imposition of an additional 5 percent power reserve is also required to accommodate engine and airframe erosion. Thus, this helicopter must be designed with a 13 percent power reserve at the design hover OGE condition (point A, figure 12). If this power reserve is used to increase the hover ceiling, we move to point B, figure 12. This excess power permits the helicopter to ascend. As altitude increases, engine power output decreases due to altitude until the power available and power required for hover OGE are equal (point C, figure 12). This establishes the new hover ceiling. The resultant hover ceiling in this example is found to be 6,200 feet pressure altitude at 95° F. ambient temperature conditions. This example also shows that the equivalent hover ceiling is dependent upon aircraft design due to the variation of climb power with rotor disc loading (figure 8).

p. <u>Alternative Forms of Expressing Vertical Flight Performance Criteria.</u> An appreciation for the various influences and contingencies which must be accommodated in the design of military helicopters and VTOL aircraft has been

FIGURE 12

VARIATION OF HOVER OGE CEILING WITH ENGINE POWER



developed in the preceding discussions. The selection of an appropriate form of expressing the resulting vertical flight performance criteria remains. Vertical performance criteria may be expressed in any of the following ways:

(1) Require the ability to hover OGE under a particular set of ambient conditions, padded sufficiently to accommodate all other "non-ambient" factors which influence vertical performance capabilities. This method is the technique traditionally employed by the Arr A specific ambient temperature and pressure altitude were used in lieu of the corresponding density altitude to accommodate the different influences of each on the engine and on the airframe aerodynamics. This method has achieved a measure of success in the past; however, its intent has often been misinterpreted. The validity of the criteria has been severely challenged on the basis of the low probability that the specified ambient conditions will ever be encountered. These challenges have succeeded in reducing the requirements in recent QMR for aircraft minimum "essential" performance to a more frequently encountered set of ambient conditions. In doing so, all margin for the other problems previously accommodated has been taken away.

(2) Establish a power reserve factor above that required to hover at some realistic set of ambient conditions. This method is an improvement over the one described in (1) above in that there are no inflated values needed to accommodate unidentified factors. The ambient conditions specified can be directly applied to the airframe design, and the power reserve can be related to the selection of an engine which has optimum partial power SFC. Furthermore, the application of flat rating the engine to minimize dynamic component strength is suggested. The major deficiency of this procedure is that the resulting airframe may be structurally inadequate to accommodate aircraft growth. It could also result in an inadequate rotor aerodynamic design if the ambient density altitude specified is overly conservative (low) or if extensive weight increases occur.

(3) Establish a lift-to-weight ratio greater than unity under a set of realistic ambient conditions. This method has been used by the U. S. Navy to accommodate gust problems while hovering over the water on antisubmarine warfare missions. It could be successfully applied to Army use by including a set of ambient conditions appropriate for Army tactical operations. The major disadvantage is that it departs from familiar terminology and does not immediately suggest the economics of airframe and SFC apparent in the method described in (2) above, and does not relate directly with the various performance modes intended. It does minimize the possibility of inadequate aerodynamic and structural design to accommodate the engine.

(4) Establish a requirement to perform specified operations such as hover and climb under realistic ambient conditions. This method is essentially the same as (3) above, except that the allowances relate directly to the actual maneuvers and contingencies intended for military helicopters, and thus the purposes and magnitudes oi the margins are more readily understood.

(5) Establish a criteria composed of two or more of the above, chosen to minimize the disadvantages of the individual constituents. This method has the obvious advantage of being able to minimize the pitfalls present in any single technique through judicious selection of two or more complementary methods. The selection of vertical performance criteria for military helicopters must identify justifiable adverse ambient conditions expressed in terms appropriate to both the aerodynamic and power variations encountered. Secondly, it must provide a power reserve to permit accomplishment of the most demanding maneuvers required during tactical operations. Finally, it must recognize the unavoidable growth in aircraft gross weight as a function of time.

5. FINDINGS

Several factors which influence the vertical performance capabilities of Army tactical helicopters have been discussed. The magnitudes of each influence has been evaluated wherever possible to provide a basis of establishing suitable performance criteria. These influences are summarized below:

a. Ambient Conditions. The various ambient surveys examined support a design "hot day" environment of not less than 4, 000 feet pressure altitude at 95° F. temperature. This 4, 000 feet/95° F. environment defines the ambient baseline upon which the vertical performance criterion may be developed.

b. Vertical Climb Performance. A requirement for a vertical climb capability of not less than 500 fpm OGE at zero airspeed was developed to permit operation into and out of congested landing zones. This capability will minimize exposure time to enemy action, accommodate wind gusts encountered in moderate turbulence and downdrafts in the wakes of preceding helicopters, provide a capability to abort the landing from a steep final approach, and provide adequate control power for maneuvering or stabilizing the aircraft.

c. Performance Deterioration in Service. The performance capabilities of any helicopter are degraded by erosion of the airframe and engine(s) accumulated during a period of service. The rate of this deterioration depends primarily upon the presence of sand and dust in operating areas, and upon protective devices incorporated on the aircraft. Maintenance practices in the more remote

areas in which Army tactical helicopters are operated may also contribute to reduced performance. Rotor blade erosion has been found to increase the power required to hover; however, this increase probably does not exceed approximately 1 percent before blades have to be replaced. Engine power available may be decreased from 4 to 9 percent by erosion before the engine is removed and replaced. Engine inlet air filters and particle separators are proving to be very effective in reducing the rate at which erosion damage is accumulated. Engine protection is specified for future Army tactical aircraft and should permit the majority of engines to achieve the scheduled overhaul interval without removal because of erosion. Thus, in instances where noticeable power losses are experienced, removal of the engine will be possible without overloading the supply system. The imposition of a 5 percent power allowance to accommodate engine erosion, airframe/rotor blade erosion, and losses attributed to maintenance problems is conservative, but should be sufficient for aircraft of the future. Allowances for power lost by the installation of engine protection devices will be included in the design of the aircraft under "installation losses" and need not be covered in the performance criteria.

d. Aircraft Weight Growth. Aircraft weight growth results from service (repairs), mission changes (expansion), and design improvements (changes incorporated during production and in service). Aircraft empty weight increases at a rate of from 1 to 2 percent per year, depending on the initial size of the aircraft and its versatility or adaptability to perform other missions. Since the Army utilizes a given aircraft model at least 10 years, empty weight increments of from 10 to 20 percent above initial design empty weight should be anticipated by the user and the developer. Since this weight is acquired over a period of years, it may be impractical to provide the full engine power and component structural margins in the initial production aircraft. The aircraft manufacturer and developing activity should, however, anticipate periodic weight increases of order of magnitude discussed by providing adequate growth potential in the design and selection of engines, transmissions, components, and airframe structure and aerodynamics. In this manner, the specified vertical flight performance capabilities may be retained throughout the service life of the aircraft.

e. Consolidated Effects. The preceding has identified specific factors which influence aircraft vertical performance. These specific factors are interrelated in such a manner as to preclude their accommodation in a simple, isolated factor approach. The use of a set of ambient conditions (e.g., 4,000 feet/95° F.) is not sufficient in itself to insure adequate vertical performance. Rather, ambient conditions may be used as a baseline upon which the other influences (i.e., allowances for maneuvering, physical deterioration, and weight growth) are added and are accommodated in recognizable form.

6. COORDINATION

A preliminary study report was prepared in September 1967, and provided to the major helicopter manufacturers and appropriate military activities for review. Comments received were used to revise this study. The findings and recommendations of the coordinated study were presented to the Commanding General, U.S. Army Combat Developments Command; Deputy Commanding General, U.S. Army Materiel Command; Office of the Assistant Chief of Staff for Force Development; and Offices of the Secretary of Defense and Secretary of the Army on 8 December 1967. It was agreed that aircraft growth potential should be recognized philosophically as a matter to be controlled by the developing activity. Thus, no magnitude would be specified in the criteria. It was also suggested that the criteria be based upon the use of Normal Rated Power to promote engine longevity. These changes were incorporated into a final draft study report published in January 1968, and are reflected in the following paragraphs of this report with the exception of 7a(3) and b. Technical analyses were conducted by the Aviation Agency using helicopter designs provided by the U.S. Army Aviation Materiel Laboratories to assess the impact of normal rated power rather than military rated power as the design requirement. These analyses indicated that the aircraft size, gross weight, and cost would be substantially increased to accommodate the larger, more powerful engine(s) installed to meet this requirement. Based on these analyses, the Aviation Agency resubmitted the study in February 1968, and requested that the power requirement reflect the use of military rated power in the interests of efficiency and economy. This revised vertical flight performance criteria study report was approved by Headquarters, U.S. Army Combat Developments Command in June 1968.

7. CONCLUSIONS

It is concluded that--

a. The following allowances should be incorporated in the vertical flight performance criteria:

(1) <u>Ambient conditions</u> of <u>4,000 feet/95° F.</u> as the baseline to accommodate both temperature and density influences on engine and airframe in areas likely to require U.S. military support.

(2) <u>Vertical climb</u> of <u>not less than 500 fpm OGE</u> at zero airspeed to minimize exposure to enemy antiaircraft fire when leaving a confined landing zone, accommodate downdrafts found in natural turbulence and in the wakes created by other helicopters, permit landings to be aborted during steep final

approaches, and provide control power for maneuvering and stabilization of the aircraft.

(3) Reserve power of not less than five percent based on engine Military Rated Power to accommodate engine and airframe erosion accumulated in service.

(4) Growth potential to accommodate aircraft empty weight increases which will be incurred over intended service life from design improvements, service repairs, and mission expansion, without loss of the specified vertical performance capabilities.

b. The following criteria, comprised of the essential vertical flight performance parameters with compensation for adverse ambient and environmental conditions, extended service use, mission expansion, and operator proficiency, are applicable for the design of Army tactical rotary wing and other V/STOL aircraft:

> "The aircraft shall be capable of hovering out of ground effect (OGE) under zero wind, 4,000 feet pressure altitude, 95° F. temperature conditions at the basic mission gross weight, and achieve a 500 feet per minute vertical climb at zero airspeed under these conditions, using not more than 95 percent of engine military rated power."

> "The aircraft shall be designed with adequate structure and growth potential in engine(s) and transmission(s) to accommodate future increased gross weight."

8. RECOMMENDATIONS

a. It is recommended that the criteria presented in paragraph 7b be adopted as the USACDC's hot day criteria for vertical flight performance to be applied to concept formulation studies, QMR, and model specifications of all subsequent Army tactical rotary wing and other V/STOL aircraft.

b. It is further recommended that consideration be given to the use of 4,000 feet pressure altitude at 95° F. ambient temperature conditions in lieu of standard sea level conditions to define those performance requirements for Army tactical VTOL aircraft which are not covered by the vertical flight performance criteria. This will provide consistency between the different performance parameters and will serve to relate aircraft specified performance to the intended mission and environmental situations.

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ANNEX A

DERIVATION OF POWER REQUIREMENTS AT HOVER

SYMBOLS

M = Rotor figure of merit defined as:

$$M = \frac{\text{power required to hover by ideal rotor}}{\text{actual rotor power required to hover}}.$$

T = Rotor thrust, lb.

P_r = Rotor power, ft lb/sec (550 ft lb/sec = 1 shp).

P = Installed engine power, shp.

η = Mechanical losses from power utilized to drive the tail rotor, transmission, etc., expressed as a percent of engine installed power.

v = Rotor downwash velocity, ft/sec.

ρ = Air mass density, slugs/ft^3
(for sea level standard conditions, $\rho_{ssl} = 0.002378$ slugs/ft^3).

σ = Ambient density ratio, ρ/ρ_{ssl}.

w = Rotor disc loading, lb/ft^2.

$$= \frac{W}{\pi R^2}.$$

R = Rotor disc radius.

$\frac{W}{P}$ = Power loading, gross weight per horsepower, lb/shp.

DERIVATION

$$M = \frac{\text{power required to hover by ideal rotor}}{\text{actual rotor power required to hover}}.$$

$$= \frac{T v}{P_r}.$$

Substituting the expression for downwash

$$M = \frac{T}{P} \sqrt{\frac{T}{2 \rho \pi R^2}}$$

Under conditions of hover, thrust = weight, thus

$$M = \frac{W}{P_r} \sqrt{\frac{W}{2 \rho \pi R^2}}$$

Substituting the expression for disc loading,

$$M = \frac{W}{P_r} \sqrt{\frac{w}{2 \rho}}$$

Solving for the rotor power required per pound of aircraft gross weight in terms of shp:

$$\frac{P_r}{W} = \frac{1}{550M} \sqrt{\frac{w}{2 \rho}}$$

This can be expressed in terms of ambient density ratio for convenience by substituting

$$\left(\sqrt{\frac{\rho}{\rho_{ssl}}}\right)\left(\sqrt{\rho_{ssl}}\right) = \left(\sqrt{\sigma}\right)\left(\sqrt{\rho_{ssl}}\right) \text{ for } \sqrt{\rho}$$

$$\frac{W}{P_r} = \frac{1}{550M} \frac{\sqrt{w}}{(\sqrt{2})(\sqrt{\rho_{ssl}})(\sqrt{\sigma})}$$

Substituting the value $\rho_{ssl} = 0.002378$ slugs/ft^3 and combining constants, the expression becomes--

$$\frac{P_r}{W} = 0.0265 \frac{\sqrt{w}}{M} \frac{1}{\sqrt{\sigma}}$$

The reciprocal of this expression is referred to as the power loading (lb/shp).

$$\frac{W}{P_r} = 37.7M \frac{\sqrt{\sigma}}{\sqrt{w}}$$

These equations define the power required at the rotor, but make no allowance for transmission and tail rotor losses which must be accounted for if we wish to relate power loading to installed engine power. This can be accomplished by replacing the rotor power term with the expression for installed power:

Installed engine power = rotor power + power losses

$$P = P_r + \eta P$$

$$P_r = P - \eta P$$

$$= P\,(1 - \eta)$$

$$\text{Thus, } \frac{P}{W} = 0.0265\ \frac{\sqrt{\mu w}}{M}\left(\frac{1}{\sqrt{\sigma}}\right)\left(\frac{1}{1-\eta}\right)$$

and power loading becomes,

$$\frac{W}{P} = 37.7M\ \frac{\sqrt{\sigma}}{\sqrt{\mu w}}\ (1 - \eta).$$

ANNEX B

DERIVATION OF POWER REQUIRED FOR VERTICAL CLIMB AS A FUNCTION OF POWER REQUIRED TO HOVER

SYMBOLS

T = Rotor thrust produced, lbs.

ρ = Air density, slugs/ft^3.

A = Rotor disc area, ft^2 ($A = \pi R^2$).

v = Air flow velocity experienced at the rotor disc, ft/sec.

v_1 = Air flow final velocity achieved downstream of the rotor disc, ft/sec.

V_c = Vertical rate of climb, ft/sec.

P_{i_h} = Induced power for hovering, shp.

P_{i_c} = Induced power for climb, shp.

DERIVATION

Newton's second law of physics states that a force is required to accelerate a mass:

$$F = ma \qquad \text{(eq: 1)}$$

The force produced by a rotor is called "thrust." Thrust can be analyzed by restating this law in terms of the change in momentum of an air mass passing through an ideal rotor disc:

$$T = (\rho A v) v_1 \qquad \text{(eq: 2)}$$

The kinetic energy per unit time imparted to the air stream flowing through the rotor by the rotor itself is:

$$\frac{K.E.}{t} = \frac{1}{2}(\rho A v) v_1^{\,2} = T . v \qquad \text{(eq: 3)}$$

Substituting eq 2 for thrust into eq 3 above;

$$\frac{1}{2}(\rho A v) v_i^{\,2} = (\rho A v) v_i \cdot v$$

Cancelling terms present in both sides of the equation, we find that--

$$v_i = 2v \qquad \text{(eq: 4)}$$

Substituting eq 4 for v_i in eq 2,

$$T = 2\rho A v^2 \qquad \text{(eq: 5)}$$

The vertical climb thrust is merely a special case of hover in which the free stream airflow has a velocity relative to the rotor disc which is equal (and opposite) to the climb rate. Thus, the climb velocity is added to the air flow rate at the rotor disc in eq. 2--

$$T = \rho A(v + V_c) v_i \qquad \text{(eq: 6)}$$

and making the velocity substitution $v_i = 2v$ from eq 4,

$$T = 2\rho A(v + V_c) v \qquad \text{(eq: 7)}$$

Eq 7 can be solved in terms of v as a quadratic expression:

$$v = \frac{\left(\frac{T}{\rho A}\right)}{V_c \pm \sqrt{V_c^2 + \left(\frac{2}{\rho}\right)\left(\frac{T}{A}\right)}} \qquad \text{(eq: 8)}$$

Rearranging eq 7 in terms of $(v + V_c)$;

$$(v + V_c) = \frac{T}{2\rho A v}$$

The power required at the rotor to produce this thrust is called induced power when rotor aerodynamic losses are neglected, and is defined as the product of thrust and the induced velocity at the rotor disc.

$$P_{i_c} = T(v + V_c) \qquad \text{(eq: 9)}$$

or, in terms of horsepower;

$$P_{i_c} = \frac{T}{550}(v + V_c) \qquad \text{(eq: 10)}$$

Eq 8 may be substituted for v in eq 10, producing:

$$P_{i_c} = \frac{T}{1100}\left[V_c \pm \sqrt{V_c^2 + \left(\frac{2}{\rho}\right)\left(\frac{T}{A}\right)}\right] \qquad \text{(eq: 11)}$$

The induced horsepower required for hover can be developed in the same manner, resulting in:

$$P_{i_h} = \frac{T}{1100} \sqrt{\left(\frac{2}{\rho}\right)\left(\frac{T}{A}\right)} \qquad \text{(eq: 12)}$$

The percent induced power required to climb as a function of the hover induced power term can be found by dividing eq 11 by eq 12

$$\frac{P_{i_c}}{P_{i_h}} = \frac{V_c \pm \sqrt{V_c^2 + \left(\frac{2}{\rho}\right)\left(\frac{T}{A}\right)}}{\sqrt{\left(\frac{2}{\rho}\right)\left(\frac{T}{A}\right)}} \qquad \text{(eq: 13)}$$

This equation (eq 13) is plotted in figure 8 to indicate percent increase above hover power required for a vertical climb speed of 500 ft/min (8.33 ft/sec) versus rotor disc loading (T/A). The use of thrust in lieu of gross weight for disc loading is to eliminate the need to consider airframe drag during the climb.

ANNEX C

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ANNEX D

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13. ABSTRACT

Various problems confronting the military operators of VTOL aircraft in tactical environments which tend to impede the ability to hover and perform related vertical flight maneuvers are examined. Several modes of flight employed under certain tactical situations were examined to establish appropriate power and lift requirements in excess of those required to hover. The influences of adverse ambient temperature, high elevation, wind, aircraft and engine deterioration, periodic aircraft weight increases, and operator skill levels are evaluated. These factors are appropriately interrelated and allowances are suggested to provide continued satisfactory vertical flight performance in service. Recommended vertical performance criteria for application in concept formulation studies, materiel requirements, and specifications for future Army tactical VTOL aircraft are provided.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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